Agriculture Canada

Research Branch | Direction générale de la recherche

Technical Bulletin 1988-4E

Phytotron manual

Canada

Phytotron manual

A.M. HARPER and D.W.A. ROBERTS
Research Station, Agriculture Canada
Lethbridge, Alberta

Technical Bulletin 1988-4E
Lethbridge Research Station Contribution No. 13

Research Branch
Agriculture Canada
1988

Copies of this publication are available from
Dr. K.W. May
Chairman, Phytotron Committee
Cereal Crop Science Section
Research Station
Research Branch, Agriculture Canada
Lethbridge, Alberta
T1J 4B1

Published by Research Program Service

Cat. No.: A54-8/1988-4E
ISBN: 0-662-15936-5

cover
The dots on the map represent Agriculture Canada research establishments.

CONTENTS

APPENDICES

FOREWORD

This publication was written primarily to provide information about the Lethbridge Research Station Phytotron for new staff members. The publication also provides an overview of some of the problems with controlling environmental factors in the Phytotron. These problems need to be considered by all scientists when interpreting the results of their Phytotron experiments.

Many scientists, engineers, architects, and administrators interested in planning new Phytotrons have visited the Lethbridge Research Station Phytotron and many have requested the type of information presented in this publication.

The authors were on the planning committee for the Lethbridge Research Station Phytotron and have been involved with it since the start of its operation in 1976. Dr. A. M. Harper, an entomologist, was Chairman of the Phytotron Committee and managed the Phytotron and the preceding greenhouse and growth chamber operations from 1970-1986. Dr. D. W. A. Roberts, a plant physiologist, was Chairman of the Controlled Temperature Rooms Committee and a member of the Phytotron Committee from 1970-1987, and was instrumental in having the first plant growth cabinets constructed at the Research Station in the 1950's.

Several books have been written on Phytotrons and their authors have discussed in detail the problems they have encountered. Consequently, the effects of radiant energy on the aerial parts of plants have been well documented. We have only briefly summarized this subject area. Since one of the interests at Lethbridge has been the area of cold hardiness and growth at low temperatures, especially of cereals, and since the problems that have been encountered in this area have not been adequately covered by other authors, these subjects are covered in detail in this publication. Our experiences should be valuable to researchers working under conditions where similar but much less pronounced problems are to be expected.

SUMMARY

Plans and physical features of the Phytotron at the Agriculture Canada Research Station, Lethbridge, Alberta, are presented, with information on its operation and management. The advantages and uses of the Phytotron and its limitations are discussed, particularly the accurate control of environmental factors. Guidelines for reporting Phytotron experiments are given and references and supplementary reading are listed.

RÉSUMÉ

Le manuel contient les plans et les caractéristiques du phytotron de la station fédérale de recherches agricoles de Lethbridge de même que des renseignements concernant son fonctionnement et sa gestion. On y discute de ses avantages et de ses utilisations et, en particulier, du contrôle précis des facteurs ambiants. On y trouve enfin des lignes directrices sur la façon de préparer les rapports sur les expériences avec le phytotron ainsi que des références et une liste de lectures supplémentaires.

INTRODUCTION

The Phytotron is a system of controlled environment facilities designed and operated for investigating relationships between plants and their environment. In the Phytotron several physical parameters of the environment including light quality and intensity, day length, air temperature, humidity, plant nutrition, and concentration of gases can be controlled.

Because the Phytotron accelerates many phases of agricultural research, results can be obtained several times faster than in the field or greenhouse. A Phytotron can be used to obtain accurate knowledge of plant reactions to environmental factors. This information is difficult to obtain in the field where these factors are variable and almost uncontrollable.

Phytotrons have been useful for studying and developing new varieties of crops that have a short growing season, are winter hardy, drought tolerant, or disease or insect resistant. They have also been valuable for studying plant physiology; insect and disease biology, development, and control; denitrification by soil organisms; plant nutrition; movement of nutrients, salts, and water in the soil; and the biology, growth, and control of terrestrial and aquatic weeds.

The Phytotron at Lethbridge Research Station was opened in 1976 and was an expansion of eight greenhouses and 16 growth cabinets that were constructed locally or were purchased between 1957 and 1970. The present Phytotron consists of 67 growth cabinets, 23 growth rooms, and 10 greenhouses.

In addition, there is a series of 22 controlled temperature rooms with limited light that are used in conjunction with the Phytotron. The Research Station also has extensive controlled environment facilities for rearing and studying insects, and for studying animal parasites on both small and large animals.

The Phytotron is available to scientists at the Research Station, visiting scientists, Post-doctorate Fellows, and graduate students working with Research Station scientists.

FACILITIES

Plant growth cabinets

There are 67 plant growth cabinets in the Phytotron of which 11 are 0.65 m^2 in growth area, 6 are 1.40 m^2, 2 are 1.67 m^2, and 48 are 3.35 m^2. All the 0.65 m^2 cabinets are a reach-in type with only one door. The 1.4 m^2 cabinets are a reach-in type with two doors on one side, the 1.67 m^2 cabinets are reach-in types with one door on each side of the cabinet, and 45 of the 3.35 m^2 cabinets are reach-in types with two doors on each side. Three of the 3.35 m^2 cabinets are a walk-in type with a vestibule on one side which gives access to the plant growth area from only the one side.

Two of the 3.35 m^2 cabinets have high ceilings (2.4 m) for growing tall crops such as corn. Five of the 3.35 m^2 cabinets have humidity control. One of these cabinets has humidification by steam and spray nozzles, and four have humidification by spray only. Four of the five cabinets have refrigeration-reheat dehumidification and the other cabinet can be fitted with a chemical dehumidifer. Two of the 1.40 m^2 cabinets are gas-tight, with gas ports, for studies with carbon dioxide or other gases. Each of the 0.65 m^2 growth cabinets and nine of the older 3.35 m^2 cabinets have air-cooled condensing units and are completely independent. The other cabinets are independent except for cooling water for the water-cooled condensing units. Each growth cabinet has a shut-off valve for the cooling water so that the unit can be repaired without affecting other units. The cooling water system is in segments so that only one or a few units need to be closed down to repair a breakdown in one of the lateral lines. If the entire system fails, units can be kept operating by connecting them directly to the domestic water supply.

The cabinets maintain accurate air temperatures ($\pm$ 0.5°C) in the range of -10 to 40°C, 5 to 40°C, or 10 to 40°C. The 13 cabinets that operate from -10 to 40°C have dual evaporators. Each cabinet has or will soon have an electronic programmer for setting and maintaining all programs. The cabinets can be programmed and monitored at the cabinet or at a central computer.

One special area of the Phytotron is the Disease-Vector Laboratory where there are three rooms. One room contains seven 0.65 m^2 cabinets, one room contains four 0.65 m^2 cabinets, and the third room is an examination and transfer room. The cabinets are used for maintaining cultures and conducting experiments with insects and mites that transmit plant diseases. The plants in the cabinets are watered by a glove-sleeve insert in the locked door, and only the scientist and the technician working with the disease and insects or mites have access to the cabinet. When the plants are to be changed the cabinet is disconnected and moved to the examination room where the vectors are transferred to new plants. The old plants and all the debris are placed in plastic bags in the room and are discarded. The room is then thoroughly cleaned and the bench top washed with alcohol. During more than 10 years of operation no areas of the Phytotron have become infested from the disease-vector area.

Plant growth rooms

There are 23 plant growth rooms with 45 plant growth beds that vary in size from 5.5 to 7.3 m^2. The total room area is 602 m^2 of which the total plant growth area is 315 m^2. The plant growth area constitutes 51% of the total room area, and the aisles, which give ready access to the plant growth area, take up the other 49% of the room area. All refrigeration, heating, programming, and other equipment are in service corridors that are adjacent to but completely removed from the plant growth rooms.

The service corridors contain nearly all the services that are needed in the rooms or by the machinery, such as electricity, compressed air, distilled water, demineralized water, and water from the community water supply. In our building the service corridor is the return duct for the building air conditioning. For this reason, the natural gas pipes are in the plant growth rooms as it is illegal to have them in the service corridor. The service corridor is also large enough to permit ready access to all machinery and removal of any part of the equipment used to condition the environment in the plant growth rooms.

Each room is completely independent except for cooling water. All rooms are now controlled by electronic programmers or will soon be fitted with them.

Most of the growth beds are approximately 1.4 m wide by 5.0 m long and many have access from both sides. The facilities were designed so that researchers would not have to reach more than 0.7 m to pick up or examine a pot or plant.

Nineteen of the plant growth rooms are 2.4 m high. Four rooms, each with two plant growth areas, are 3 m high to permit normal growth of tall crops such as corn, and for the study of soils where plants are grown to maturity in large containers with a soil depth of 1 to 1.5 m. One room has a specially reinforced floor to withstand the weight of large amounts of soil.

Tanks for controlling soil and air temperatures separately are available in four growth rooms. The soil temperature is controlled in narrow tanks by temperature-controlled water in which the pots are almost fully immersed. Air around the plants is controlled by the vertical movement of air from growth benches beneath the tanks. The plumbing for the soil temperature control can be readily removed and the beds can be used as normal plant growth beds.

Greenhouses

There are 10 greenhouses with 45 compartments and a total area of 1950 m^2. Greenhouses are single-glazed, and each compartment has supplementary heating, lighting, and cooling with evaporative coolers. One greenhouse compartment has an electronic controller that controls the temperature more accurately than in the greenhouses with thermostats only. It opens

and closes the vents and controls the supplementary heating, cooling, and lighting. During the summer some of the greenhouses are shaded with metal blinds, and some with whitewash. None of the greenhouses is cooled by mechanical refrigeration because of the cost. The heating system is adequate to maintain the required temperature for plants when the outside temperature is at -40°C.

Benches in all greenhouses are metal and all floors are concrete. When high humidity is needed in a greenhouse, water is sprayed on the floor several times a day, or electrical humidifiers are placed in the compartment. Metal benches and concrete floors are used for cleanliness and to make the control of insects, mites, and diseases easier.

Controlled temperature rooms with limited light

Associated with the Phytotron are 23 rooms with controlled temperatures and limited light. (See Appendix 4 for room temperatures and dimensions.)

Twelve of these rooms are maintained at constant predetermined temperatures and divided equally into two groups. One group usually contains rooms at 25, 20, 15, 10, 5°C, and a spare. The spare room is used at various temperatures usually near the freezing point with the proviso that if one of the other rooms breaks down the scientist using the spare room must vacate it immediately. The spare room is then set at the temperature of the room that failed and maintained there permanently or at least until repairs are made. Often the room that failed becomes the new spare room. Rooms in the other group are run at 0.7 to 0.8, -5, -10, -15, -20°C, and a programmable low temperature. One room is run at 0.7 to 0.8°C instead of 0°C to avoid freezing of exposed moist soil or vermiculite as explained later in the section on cold rooms. These rooms require frequent defrosting and are operated with defrosts every 4 hours. The programmable low temperature room is used for studies on low temperature pathogens (snow molds). It has a programmer that permits gradual controlled lowering of air temperature and its evaporator is designed to reduce the frequency of defrosting.

One cold room provides extra cold storage at -20°C and two others provide storage at -40°C. A third room at -40°C is reserved for storage of pesticide-laden material from the field that is awaiting chemical analysis.

Two rooms are designed and operated for vegetable storage at temperatures just above freezing. These rooms have additive humidity control (steam generators). With the changing research program these rooms are now operated at 1 and -10°C ($\pm$ 0.5°C) and are used in a program to select cold-resistant lines of winter wheat. This change illustrates the possibilities of adapting a controlled temperature room facility to changing research requirements.

Three other rooms are operated just above the freezing point (4 to 5°C) for storage of insect-damaged plant material and diseased plants. One of these rooms is used for diseased potato storage and has additive humidity control (steam generator).

One programmed cold room is used to freeze plants in connection with studies on hardiness. It has an evaporator which is designed to provide long periods (4-5 days) between defrosts at sub-zero temperatures rather than the 4 hours between defrosts in the 12 temperature rooms described above. The cold room with the long period between defrosts does not provide temperature control as accurate as in rooms with the short time between defrosts.

Finally, there is a seed storage room which is run at 5°C. This room has a dryer that keeps the relative humidity below 20%. It is used only for long-term storage of genetic stocks. All seed material is inspected for pests before it is placed in the room and yearly thereafter. Infested material found in the room is removed and treated to destroy the pests before it is returned to the room.

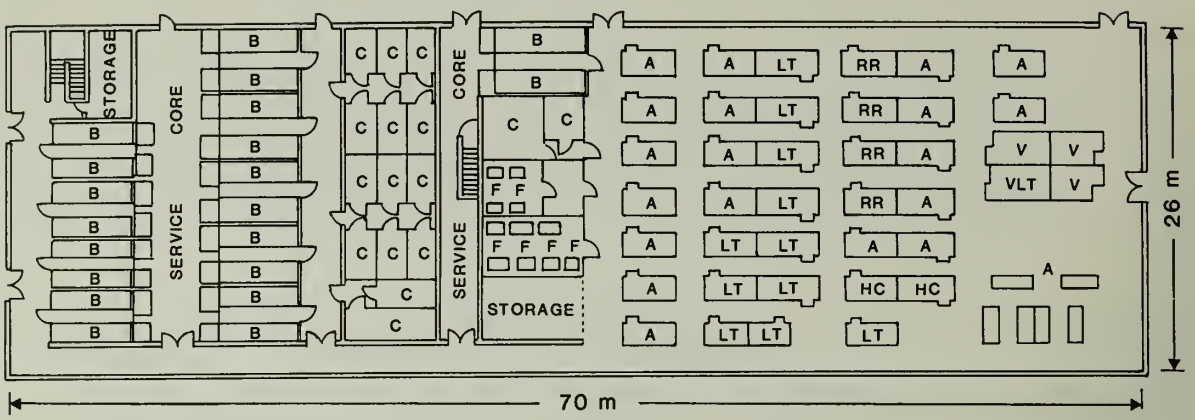
Headerhouse facilities

The following rooms and areas are in a headerhouse adjoining the main portion of our Phytotron and are used in conjunction with it:

Vegetable research laboratory
Plant physiology laboratory
Insect and disease assessment laboratory
Plant dissection, examination, and washing laboratory
Equipment and plant washing room
Seed storage room (temperature and humidity controlled)
Pesticide-laden plant storage room (-40°C)
Garbage storage room (air-conditioned)
Incinerator room
Plant drying room (small and large dryers)
Plant nutrient preparation room
Pot and material storage rooms
Plant spray room
Fungicide, insecticide, and fumigant storage room
Autoclave
Soil and plant grinding room (with special dust removers)
Soil storage and mixing rooms
Storage room for special soils in containers
Equipment maintenance room
Potting, seeding, and examination benches

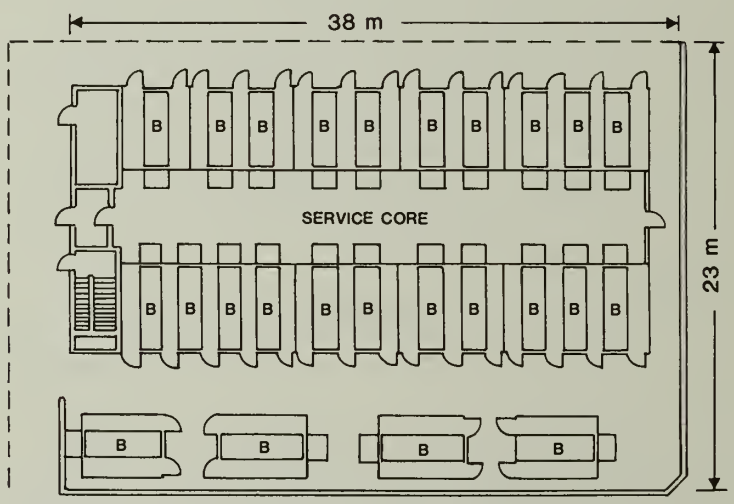
Service trucks can be driven into the main area of the headerhouse to load and unload materials. Soil is loaded into the soil bins through doors to the exterior that open into each bin.

PLANS OF PHYTOTRON AREA



A = standard cabinet (5 to 40°C)
B = growth bench (5 to 40°C)
C = temperature room, limited light (-40 to 40°C)
F = air-cooled small cabinets in disease-vector room (5 to 40°C)
LT = low temperature cabinet (-10 to 40°C)
RR = controlled humidity cabinet (refrigeration reheat) (5 to 40°C)
HC = high ceiling cabinet (5 to 40°C)
V = vestibule (5 to 40°C)
VLT = vestibule, low temperature (-10 to 40°C)

MAIN FLOOR
SERVICE WING



B = growth bench (5 to 40°C)

BASEMENT
SERVICE WING

BASIC CONSIDERATIONS FOR CONTROLLED ENVIRONMENTS

Benefits of controlled environments

The introduction long ago of the greenhouse started freeing the plant scientist from the vagaries of the field. In the last 50 years in Canada the development of completely artificial environments for growing plants has provided a quantum leap forward in this direction.

The first, but probably not the most important, advantage of the Phytotron is its capacity for the production of crops on a year-round basis in northern climates. Furthermore, uniform materials for biochemical, physiological, entomological, pathological, and genetic studies can be produced so that experiments can be planned and spread over the entire year, as desired, to utilize staff efficiently. This stands in strong contrast to the greenhouse where wintertime production of plant material is often limited by short day lengths and low light intensities. Greenhouse production in summer requires supplementary cooling.

In a Phytotron it is possible to adjust conditions so that hybridization can be done at any time during the year and good seed set can be obtained for early generations of a breeding program. This shortens the duration of breeding programs by several years. Consequently, a new generation may be started very soon after the parent plants set seed. In this way three generations per year of cereals and six generations of faba beans can be obtained.

Controlled environments are advantageous for pathological studies since environmental conditions often control infestation and may alter resistance, such as with cereal bunt or disease expression in ring rot of potatoes. With controlled environment facilities it is possible to identify the environmental factors influencing the changes in resistance or disease expression.

The greatest advantage to be gained from the use of the Phytotron is the control of growing conditions. Controlled environment facilities have, for example, made possible a much more accurate picture of the conditions that affect cold hardening of wheat in the field. The use of such facilities has made it clear that there is more to temperature effects than just increased hardiness with lowered temperature within specified limits. These facilities have made possible an explanation of why killing occurs in late winter and early spring and have permitted the development of a technique for testing hardiness which can be used to select for resistance to such killing.

Detailed work on the genetics of cold hardiness in wheat is an example of a study that would be almost impossible without controlled environment facilities for hardening and hardiness testing. In the field, winterkilling is variable from one part of a field to another and is often all or none. Many tests are lost because of a lack of differential kill. Winters are sufficiently variable and unpredictable that it is impossible to select a site that will give consistent winterkilling due to low temperatures. Furthermore, in the field winterkilling may be

caused by disease. Differential kills on tender material for genetic studies require short mild winters, whereas long cold winters are required for differential kills on very hardy materials. Such places in the field are usually widely separated, often by hundreds of miles.

In order to gain maximum advantages from the use of a Phytotron, its operation and limitations must be understood. This understanding is essential for the proper interpretation of experimental results. For this reason these limitations are discussed in detail in the section on environmental conditions. It is the authors' hope that this discussion will lead to the design of special equipment to overcome some of the limitations and so make possible a better understanding of the effect of the environment on plant growth and crop production. Such an understanding should eventually assist the plant breeders in developing more productive cultivars.

Refrigeration systems

It is advantageous for persons using the cold rooms and growth facilities to understand the basic principles involved in refrigeration systems. Figure 1 shows the main components in a simplified system which consists of a pump, condenser, receiver to store liquid refrigerant, expansion valve, and evaporator.

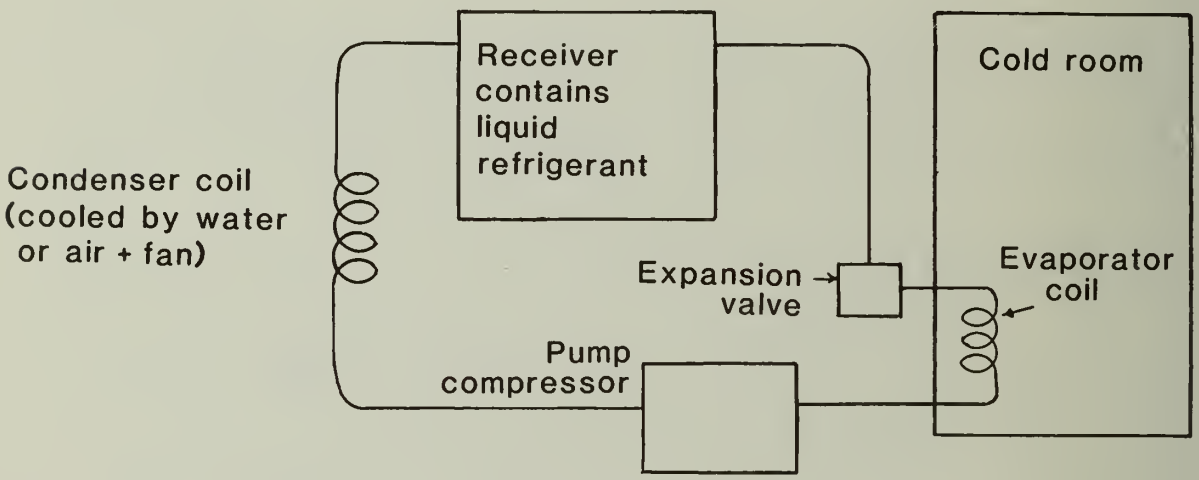


Figure 1: Basic refrigeration system.

Provision for thermostatic temperature control of the space to be refrigerated is included in working systems. Such systems have a dryer to prevent any water vapor from freezing inside the system and plugging it with ice. Other protective devices and refinements are usually incorporated.

The pump or compressor compresses the refrigerant gas. As it does so the gas warms up. The hot gas under high pressure is passed through the condenser where it is cooled and condensed into liquid. Cooling of the gas is achieved by circulating cold water or cold air around the outside of the condenser coils. The chilled refrigerant liquid under pressure is stored in the receiver until it passes through some type of control mechanism (commonly an expansion valve) which sprays it in the form of liquid droplets into the evaporator coil in which the compressor maintains a low pressure.

The liquid refrigerant evaporates in the evaporator and the resulting gas expands owing to the low pressure. Both evaporation and expansion require that the refrigerants absorb heat and this results in a drop in temperature in the evaporator. The evaporator is situated in the space to be cooled or in an air duct supplying cold air to the space to be cooled. The compressor evacuates the cold refrigerant gas from the evaporator, compresses it, and passes it on to the condenser to repeat the cycle. The physical properties of the refrigerant gas place constraints on the temperature range over which it may be used for refrigeration: R 12 works easily down to -20°C but can be used to -30°C; R 22 works easily down to -30°C but can be used to -40°C; R 502 works easily down to -40°C but can be used to -50°C; R 292 (propane) + R 503 (freon) work well from -50 to -130°C when used in a cascade refrigeration system.

In practice, the temperature of the evaporator coil must not vary too much or else the air temperature in the cabinet cannot be held constant. In order to achieve this, some hot compressed gas is bypassed from the pump directly into the evaporator. The evaporator temperature is controlled by regulating the cycling of hot gas and cold refrigerant.

In most working cold rooms the evaporator removes heat from the air in the cold room. The system is thermostatically controlled to keep the air in the cold room within a specified temperature range. When warm material is moved into the cold room, heat flows from the warm object to the room air to the evaporator. This means that the air temperature in the room rises. As long as the amount of material moved into the room is small or the temperature of the material is only a few degrees above room temperature, the rise in air temperature will be small. However, if a large amount of material at room temperature is transferred into a low temperature room, the air temperature in the cold room will rise several or even many degrees above the set temperature. The air in the room will remain above normal until most of the heat in the material has been transferred by convection to the evaporator. Rate of heat transfer will depend on the specific heat of the air (a fixed quantity) and the rate of air movement. If a large amount of warm material is moved at once into a cold room, the air temperature in the room will remain above normal for

several hours. Where accurate control of the room temperature is required, these effects must be avoided either by prechilling the materials to be placed in the room or by moving in small amounts of the material at suitably spaced intervals.

Moving large amounts of cold material into a warm room will produce similar effects except that the room temperature will fall rather than rise. If very rapid chilling is required, the evaporator coil may be connected to a metallic plate. The material to be chilled is placed on the metallic plate which conducts heat from the material to the evaporator without the need for convection currents in air. Such a system is of no advantage if a whole room is to be chilled.

Controlled temperature rooms are usually sealed to reduce leakage of warm or cold air into them from the environment and they are insulated to reduce heat transfer through the walls and doors. This makes possible much better temperature control within the room and reduces the power required to maintain the room temperature. Room doors should be kept closed as much as possible.

Because the rooms are sealed dry ice (solid carbon dioxide) and liquid nitrogen should never be stored in an enclosed cold room. Both these materials will vaporize and the level of carbon dioxide or nitrogen in the room will rise. If the level of carbon dioxide rises above 10% it will cause persons exposed to it to become unconscious. In a cold room this can result in death either by poisoning or hypothermia. High levels of nitrogen result in asphyxiation and death.

In order to chill a cold room or growth cabinet to a temperature below the freezing point, it is necessary to chill the outer surface of the evaporator coil to a temperature below 0°C. Under such conditions any water vapor in the cold room will be deposited as frost or ice on the evaporator and will build up to the point where it plugs the evaporator and stops air flow through it. Room temperature will then rise because convective cooling has been cut off.

In practice, because water freezes at 0°C cold rooms cannot be maintained indefinitely much below 4°C with a single evaporator if really accurate temperature control is required. This problem is aggravated in a growth room or growth cabinet where energy must be added as light during at least part of the daily cycle. The best solution to this problem for research purposes is to use two evaporators. One is used to cool the room while the other is isolated from the room and warmed either electrically or by hot gas from the refrigeration system. This heating removes the frost and ice. This system is expensive and requires a system of mechanical dampers to isolate the evaporator being defrosted. It is, however, the only system that will provide accurate temperature control below 4°C in cold rooms. It is also the only system that can be used in growth cabinets if plants are to be grown under continuous light at low temperatures and if air temperatures are to be maintained accurately at temperatures below 5°C. In cold storage rooms where brief (up to 15-20 minutes) warm periods can be tolerated, a single evaporator may be used. When this evaporator coil is defrosted, air circulation is

cut off to the room. This system works well for cold temperatures near and just below the freezing point, but below -15°C it rapidly becomes unsuited to research needs as the temperature rises during defrost become progressively bigger and longer. With single coil systems the frequency and duration of defrosting is controlled by:

(1) the amount of moisture to be introduced into the system with the material to be refrigerated,
(2) leakage of water vapor into the room from a door opening or into the growth cabinet from the ambient air through cracks and seals around the doors (growth cabinets cannot be air-tight or carbon dioxide levels would fall too low for plant growth), and,
(3) the design of the evaporator coil and refrigeration system.

Good design makes possible several days of sub-freezing operation for application of cold stresses to test the hardiness of cold hardened plant material. For such work, excellent room design is also needed to prevent the development of layering of the air (producing a temperature gradient) and cold spots within the room. Cold hardened plants are extremely good thermometers and will react to temperature differences of as little as a few tenths of a degree C.

Temperature measurement

Temperature control is an important feature of a controlled environment facility. Several devices are used for temperature measurement and these differ considerably in speed of response. A measuring device with slow response time may show a greatly reduced range of fluctuation in temperature in an environment with rapidly varying temperature. For example, the apparent magnitude of the high temperature spike occurring during defrost in a low temperature cold room lacking a dual evaporator will be greatly reduced while its duration will be increased as the speed of response of the temperature-measuring device decreases.

Of the devices used for temperature measurement, liquid bulbs (e.g., glass-alcohol or glass-mercury thermometers and some of the older style chart recorders) and bimetallic strips have slow response times. Their use tends to conceal the poor temperature control of cold rooms operated below -15°C without dual evaporators. Well designed thermistors have much better response times but have a linear response to temperature only over narrow temperature ranges. This problem can be overcome by proper electrical circuitry. Resistance bulbs (resistance wire wrapped around ceramic) can be designed with moderate response times and are useful where it is desirable to average a rapidly fluctuating temperature. Thermocouples (especially ones made with very fine wire) have rapid response times. For best results, the actual thermocouple and a length of lead wire should be in the same temperature environment. This reduces the heat conduction between the environment of the leads and the actual junction. This precaution increases accuracy when the leads must pass through environments with widely differing temperatures. Thermocouples work conveniently with chart recorders, digital displays, dataloggers, and computers.

Light

The description and measurement of light provided to plants present special problems. Light is radiant energy in a certain portion of the electromagnetic spectrum. For the present purposes it encompasses radiation with wavelengths from 290 mμ to 850 mμ, those wavelengths that affect plant growth. Different groups of wavelengths provide the energy for different processes within the plant. Some of these processes have been little studied. As a result, investigators cannot be sure of what should ideally be measured.

The most important process in plants requiring light is photosynthesis, which is responsible for providing the energy required for plant growth. In higher plants, chlorophylls **a** and **b** are the pigments that absorb the light for photosynthesis. These pigments absorb in the blue and red portions of the spectrum. Among angiosperms, the synthesis of the chlorophylls and of the chloroplasts themselves is light-dependent. Both light intensity and quality appear to be involved in regulatory effects. The conversion of protochlorophyllide to chlorophyllide **a** is light-dependent in the angiosperms (absorption bands in blue and red).

Phytochrome is another important plant pigment system. It is involved in the regulation of plant growth, especially in seed germination in some species, dormancy in woody plants, and in the photoperiodic control of flowering. The pigment exists in two interconvertible forms. One form absorbs in a band around 660 mμ (P_r) and the other in a band around 730 mμ (P_{Fr}). P_{Fr} is slowly converted into P_r in the dark. It is the proportion of these two forms in the plant that determines the growth responses of the plant. The proportion and timing of application of these wavelengths in the diurnal cycle are therefore important in regulating plant growth.

Plants also contain other pigments such as flavins and carotenoids that absorb light in the blue end of the spectrum. Phototropism is one system activated by such light. The pigments involved have not been identified with certainty. Other light-sensitive systems may exist and may be detected by comparing plant growth responses in the field with those in the greenhouse or growth cabinet.

Light intensity and total energy received per day are also known to affect plant growth. Responses known as HER or high energy responses occur, but little is known about them except that high light levels are required for their initiation.

Day length, the proportion of the normal 24 hour day in which light is supplied, is also very important in regulating rate of development of many species. The phytochrome system is involved in those responses.

The multiplicity of light-sensing systems in plants greatly complicates the already difficult problem of measuring the light supplied to the plants.

Three units developed for different purposes are in common use for measurement of incident light energy. These are the lux (1 lux = 0.093 foot-candles), the microeinstein per second per square meter ($\mu E\ sec^{-1}\ m^{-2}$), and the watt per square meter (W/m^2).

The lux (1 lumen per square meter) and foot-candle (1 lumen per square foot) were units developed by lighting engineers to measure illumination for situations in which the ultimate light receptor is the human eye. The standard human eye is most sensitive to yellow light of 555 mμ. Equipment for measuring illumination is readily available. However, some of it is not very accurate.

Measurements of illumination have been criticized by plant scientists because the spectral responses of the human eye and plants are not similar. However, the same criticism applies to both the other units of measurement of incident light ($\mu E\ sec^{-1}\ m^{-2}$ and W/m^2) since neither of these units evaluates the energy from different wavelengths in the same way as a plant does. The only inexpensive solution to this problem is to specify exactly the light source used and to include data on voltage and power. For fluorescent light, the phosphor should be specified (e.g., cool white, daylight, wide spectrum grolux, etc). If more than one source is used (e.g., cool white fluorescent and incandescent), separate data for each of the sources should be provided.

The microeinstein $sec^{-1}\ m^{-2}$ is a unit developed to measure photon flux by scientists interested in photochemistry. Radiant energy (including light as defined above) is considered to be made up of discrete particles called quanta or photons. The energy of a photon depends on its frequency (inverse of wavelength) according to Planck's law ($E = hv$) where E = energy in ergs per sec, $h = 6.62 \times 10^{-27}$ ergs per sec (Planck's constant) and v = frequency in cycles per sec. A consequence of this is that photons of different wavelengths or frequencies carry different amounts of energy. One molecule can absorb one photon at a time. Ideally, a condition seldom realized, if a gram molecule (mole) of photochemically reactive substance absorbs 6.022×10^{23} (the number of molecules in a mole) photons or quanta of light, it should become activated to produce a mole of product. An einstein is 6.022×10^{23} (Avagadro's number) photons, a sufficient number of photons to activate 1 mole of photochemically reactive compound.

The $watt/m^2$ is the unit used by physicists to measure irradiance or power per unit area.

Many workers use the term PAR or photosynthetically active radiation. It measures the irradiation in the 400-700 mμ waveband in W/m^2 or the photon flux density in the same waveband in $\mu E\ sec^{-1}\ m^{-2}$. This sort of measurement ignores the formative effects of different wavelengths on plant growth.

The ideal solution to the problem of light measurement would be to provide a plot of wavelength against incident energy to cover the whole spectrum of interest for plant growth. This solution has serious disadvantages in that the necessary equipment is expensive and reporting of the results requires a table or graph.

Accurate interconversions among these units are complicated (see Appendix 14) and require accurate information about the spectral distribution curve of the radiant energy from the source. Approximate conversions may be made using empirical factors tabulated by McCree (1981), but such conversions require a knowledge of the light source.

In practice, the maintenance of a nearly constant light level in a growth cabinet requires constant monitoring. Light bulbs, both fluorescent and incandescent, burn out. Ballasts for fluorescent lights fail. The light output of fluorescent lights decreases with age. The drop is rapid during the first 100 hours of operation and the rate of drop gradually decreases subsequently. The ideal solution to these problems would be to mount a photocell inside the growth cabinet and connect it to a recorder or digital output.

The light output of fluorescent lights is temperature-dependent. It drops off at high temperatures (above 35°C) and at low temperatures (below 10°C). Since it is the actual tube temperature that is critical, the limits for operation to provide adequate light output will depend on air circulation around the lights.

For really critical work on light quality, the spectral distribution of the radiant energy should be checked periodically. There have been reports of changes in the spectral distribution of output from at least some of the more specialized fluorescent lights.

Humidity

Control of the amount of water vapor in the atmosphere of a growth cabinet is important because it influences the transpiration rate of the plants in the chamber. Transpiration rate is partly determined by the difference between the water vapor pressure inside the leaf and that in the ambient air, assuming that air circulation around the leaves is rapid enough to prevent the formation of a layer of air surrounding the leaves with a relatively high vapor pressure. The vapor pressure within the leaves will normally be close to that of water at the same temperature. The vapor pressure of water rises rapidly as the temperature rises.

Relative humidity is the amount of water vapor in the air expressed as a percentage of the maximum amount of water vapor that the air could hold at the given temperature. Since the water vapor holding capacity of air rises with temperature, a rise in temperature of the air will cause a drop in relative humidity if the absolute amount of water vapor in the air remains constant. This explains why, in a growth cabinet with rapid temperature cycling (hunting), comparable rapid cycling of relative humidity occurs. The relative humidity will drop as the temperature rises and rise as the temperature drops.

Four general methods are available for measuring relative humidity. First, there is determination of dew point. This type of method determines the temperature at which the air is saturated with water vapor. It is accurate but rather expensive. It may be used to monitor

conditions in a growth cabinet. Second, there are the wet and dry bulb thermometers, thermocouples, or thermistors. These measure the maximum temperature drop that can be caused by evaporative cooling in the atmosphere. Relative humidity is then determined from tables (Weast et al. 1985-86). This technique can be used for measuring or monitoring the relative humidity in a growth cabinet. It is accurate and works well as long as the wick on the wet bulb sensor can be kept fully moistened with pure distilled water. The third group of methods depends on the change in physical properties (e.g., length of hairs, or electrical resistance of hygroscopic salts such as LiCl) of materials as the relative humidity of the surrounding air changes. This type of unit requires careful calibration. Some units of this type are suitable for controlling and monitoring humidity in growth cabinets. The fourth method for measuring relative humidity is by infrared detectors. These are accurate but expensive. They depend on measuring the quantity of water vapor in the air by its ability to absorb infrared radiation of certain wavelengths.

Four methods for humidity control are available at Lethbridge: refrigeration-reheat, chemical dryer, additive, and plastic bagging.

With properly designed equipment, refrigeration-reheat is an accurate method for controlling humidity. It relies on removing excessive moisture from the air by chilling the air in the evaporator coils. The air temperature is then raised by introducing hot refrigerant gas into the evaporator. Temperature control is achieved by proper cycling of hot gas and cold refrigerant into the coil. The air to be chilled must be moist enough that water will condense on the evaporator coils when the air is chilled to the dew point. Proper evaporator design is also necessary to make sure that all the air leaving the evaporator is at the dew-point temperature.

Chemical dryers are used where low relative humidities are required. These use a hygroscopic chemical to remove water vapor from the air. The chemical is usually regenerated by heating.

Additive humidity control is useful only when relative humidity must be raised above the fairly dry conditions usually present in a growth cabinet. A humidity sensing unit controls addition of water by a misting or atomizing device or in the form of steam. Pure water (demineralized or distilled) or steam (not containing fungicides, bacterocides, and pH control chemicals often used to protect the condensate return lines) must be used.

In plant disease research, relative humidity levels close to 100%, sometimes with dew present, are often required for infection studies. These levels can be obtained in growth cabinets by covering the plants with plastic bags, preferably in the dark. In the light, difficulties may be encountered with radiant heating. In a growth room this system can be scaled up and a plastic tent and humidifiers can be used to permit handling the large populations needed in plant breeding programs. It is especially useful where temperature control is required for good infection.

ENVIRONMENTAL CONDITIONS

Cold rooms

In controlled temperature rooms with minimum light (below 1 klx), it is usually assumed that all points within the room are at the same temperature. For critical work, this assumption should be tested by simultaneous temperature measurements using thermocouples and a recorder or datalogger of some type. The actual pattern of air movement within the room will determine how closely this assumption is realized. Very serious discrepancies (several degrees C) may occur in badly designed rooms. Placement of large amounts of material within the room may also affect patterns of air flow and temperature uniformity.

Operation of a controlled temperature room at the freezing point poses special problems for biological research if the material must not freeze. Experience at Lethbridge shows that moist soil or vermiculite exposed to room air will freeze at air temperatures slightly above the freezing point even though stoppered flasks of distilled water in the same room do not freeze or supercool. This problem arises because the air movement in the room, which is essential for temperature uniformity, causes evaporation from the moist surface of the soil or vermiculite. Water must absorb heat in order to evaporate. Thus, heat flows from the soil or vermiculite to the water to facilitate its conversion from the liquid to the gaseous state and, in the process, the soil or vermiculite is chilled below the freezing point and the water in the medium freezes. The chilling is maintained after the soil freezes because water vapor continues to be formed by ice sublimation. Our solution to this problem is to raise the air temperature in the room. For our rooms, a temperature of 0.7 or 0.8°C is required to prevent exposed moist soil or vermiculite from freezing. An alternate solution to the problem would be to cover the surface to prevent the evaporative cooling.

Plant growth cabinets and rooms

INTRODUCTION The purpose of growth cabinets and growth rooms is to provide controlled, reproducible conditions for plant growth. At first glance it would appear that all that is required is to set the air temperature, intensity and duration of lighting, and relative humidity. For many experiments, reasonably reproducible results may be obtained by doing this, provided that the plants are to be grown at 20 to 25°C and that high light intensities and close humidity control are not required. If plants are to be grown under conditions such that a small change in conditions causes a measureable change in plant growth, then reproducible results are difficult to achieve in growth cabinets. However, overall trends can easily be detected but not quantified accurately.

We have not studied these problems extensively at Lethbridge but have made some measurements that illustrate the magnitude and nature of the problems that will be encountered. Part of the data comes from work on cold hardening of wheat.

Under cold hardening conditions, rate of growth and length of leaves are very sensitive to small differences in mean temperature. Furthermore, it is probably true (Peacock 1975) that the apical meristem is the site of temperature reception, at least for control of leaf length. The meristem of young wheat plants is located below the surface of the growth medium. Although we have not performed replicated or even repeated experiments on the true microclimates, our experiences indicate the need for extensive serious research into the problems to be encountered.

Temperature, light, humidity, air movement, watering, containers, nutrition, carbon dioxide, other gases, media and nutrients, diseases and pests will be discussed to the extent of our experiences. Temperature and humidity are probably the most difficult to control. Good humidity control requires good temperature control. The temperatures experienced by the aerial parts of the plant depend on several factors: air temperature, air velocity, humidity, water status of plants, and light. The temperature of the below-ground parts of the plant will depend on air temperature, air velocity, watering, water content of growth medium, light, and container configuration.

TEMPERATURE Measuring temperature in a cabinet where high levels of light are supplied for part or all of the daily cycle presents special difficulties because air movement is required to maintain temperature.

It is conventional to measure air temperature at a site which is protected from the lights. In Conviron growth cabinets this is achieved by removing a small stream of air from a central location in the cabinet and passing it over the sensing unit, which is located in the machinery compartment. If an exposed thermometer is mounted in a growth cabinet in the light cycle, it will be observed that the temperature is higher closer to the lights. This response is caused partly by radiant heating of the thermometer and partly by air temperature. Plant leaves will experience this effect and its magnitude will depend mostly on the quality and intensity of the light supplied.

Although the aerial parts of plants are surrounded by air, they are not necessarily at the same temperature as the ambient air. These relationships and the measurement of leaf temperature are discussed by both Salisbury and Tanner (see Tibbitts and Kozlowski 1979). Although we have done no work in this area, a summary of the situation is useful.

Even if the air temperature is kept constant during the light and dark periods, there is no reason to expect that the plants will experience a constant temperature throughout the day. Plants will probably respond to the temperatures of their parts rather than to the ambient air temperature even though the latter will have a large effect on plant temperatures. In the light period the leaves will absorb a considerable amount of the energy radiated by the lights. This energy will be converted to heat which will raise the temperature of the leaves. Since the light intensity is not the same in all parts of a growth cabinet, these heating effects will be uneven.

Many but not all plants open their stomata during the light period. This serves two purposes. It allows uptake of carbon dioxide for photosynthesis and sugar manufacture and for evaporation of water for cooling. This evaporation powers the transpiration stream for transfer of mineral nutrients from the growth medium to the leaves. Since evaporation of water requires that the water molecules take up heat, evaporation will cool the leaves. This cooling will be influenced by a number of factors, some of which vary among plant species. These factors include:

(1) internal leaf structure and abundance of stomata,
(2) whether stomata are open or closed (controlled chiefly by light and water status of the plant),
(3) water vapor pressure gradient between air in the interior of a leaf (usually close to saturation) and exterior air. This gradient will be influenced by relative humidity of ambient air and air movement over the leaf surface,
(4) temperature (higher temperature means higher transpiration), which changes water vapor pressure gradient and affects stomatal movement, and
(5) water status of plants, which is affected by availability of soil water.

Orientation of leaves will affect the amount of radiant energy and consequently the leaf temperature. As the plants grow, additional leaves will be produced and these will usually shade the lower leaves thereby reducing the light energy that they receive and consequently their temperature.

During the dark periods it is to be expected that leaf temperatures and air temperatures will be similar except in those species (e.g., succulents) with stomata open at night and those with a cuticle so thin that appreciable water loss occurs through the cuticle. Where appreciable water loss occurs from leaves in the dark periods, leaf temperatures will be below air temperatures because of evaporative cooling.

Some factors that influence the temperature of the growth medium are container geometry, radiant heating, evaporative cooling, moisture content of growth medium, watering, cycling of air temperature, and size of plants.

One of our first experiences with these problems involved container geometry. Wheat was being germinated and cold hardened at a constant 2°C under a 16 hour day of approximately 16 klx, provided by cool white fluorescent tubes plus a small incandescent supplement, in a vermiculite medium watered three times a week. Some of the plants were growing from seeds sown approximately 1 cm deep in wooden flats 25 x 39 x 9 cm filled to a depth of 7 cm with vermiculite. The others were growing in the same medium with the same watering schedule in green plastic pots (top diameter 15 cm, bottom diameter 10.3 cm, height 14 cm) beside the flats in the same growth cabinet. Plants in the plastic pots took 2 weeks longer to emerge. Crown temperatures in the plastic pots were not checked but were probably colder.

Moist soil surfaces may be chilled by evaporative cooling in the dark period or, if heavily shaded, by the plant canopy. During the light period, exposed soil surfaces are warmed by radiant heating.

If the plants are watered with nutrient or distilled water that is much warmer or colder than the temperature of the growth medium, then the temperature of the medium will rise or fall respectively. This disturbance will persist for several hours (Fig. 2). Properly chilled water or nutrient for watering cannot be produced by storing it in the growth cabinet in which the water or nutrient is to be used as long as there is a light period in the cabinet. Under such circumstances, radiant heating will warm the nutrient.

In a growth cabinet with an air temperature of 7°C and continuous light of 21.5 klx supplied from cool white fluorescent plus incandescent light, several temperature measurements were made. The temperature of nutrient in an unshaded carboy was 15.5°C. The temperature (mercury thermometer calibrated at 0°C with ice-distilled water) under an empty (no plants) flat of vermiculite was 7.3°C, on top of the flat it ranged from 10.5 to 14.5°C (exposed), and a thermocouple at about 1 cm depth showed 16°C. A comparable flat containing a heavy canopy of 9-week-old wheat plants grown at 7°C with continuous light gave a temperature of 9°C at plant crown level (Fig. 2). This provides a dramatic example of the effect of shading the surface of the medium on the temperature of the medium under lights.

Similar shading responses and appreciable variability were observed in experiments similar to the above except that the air temperature was maintained at a constant 3°C (under 21.5 klx of continuous light). A flat with 4- to 5-week-old seedlings showed crown temperatures of 7°C. Differences in crown temperatures of 2 to 3°C have been observed in plants grown in flats under apparently similar conditions. Differences in plant growth have been noted under these conditions.

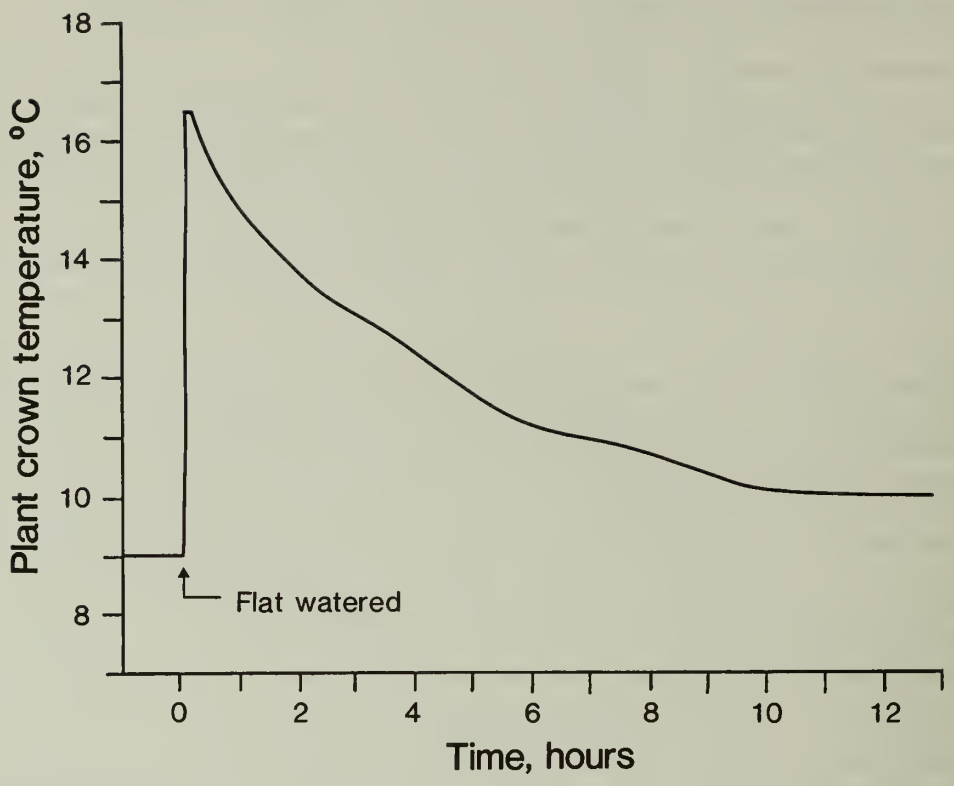


Figure 2. Effect of watering with nutrient at 20°C on crown temperature of 9-week-old plants grown in medium grade vermiculite in flats 25 x 35 x 9 cm filled with 7 cm of vermiculite. Plants were grown at a constant temperature at 7°C under 21.5 klx of cool white plus incandescent light continuously.

For a proper study of leaf length (a trait correlated with cold hardiness) of wheat grown under cold hardening conditions, these temperature aberrations will have to be controlled. One requirement will have to be that nutrient or water used for watering is prechilled in a dark cold room run at the proper temperature.

Figure 3A shows data on crown temperatures of wheat plants being cold hardened under a regime frequently used at Lethbridge. This regime provides 8 hours of darkness at an air temperature of 4°C and 16 hours of 9.7 klx of cool white fluorescent plus incandescent light with an air temperature of 6°C. Minimum dark-period crown temperatures approximated minimum air temperatures but maximum light-period crown temperatures were 4°C higher than maximum air temperatures. The evaporative cooling effect in the dark was not detected and was probably relatively small in this test, but radiant heating effect was quite large (4°C).

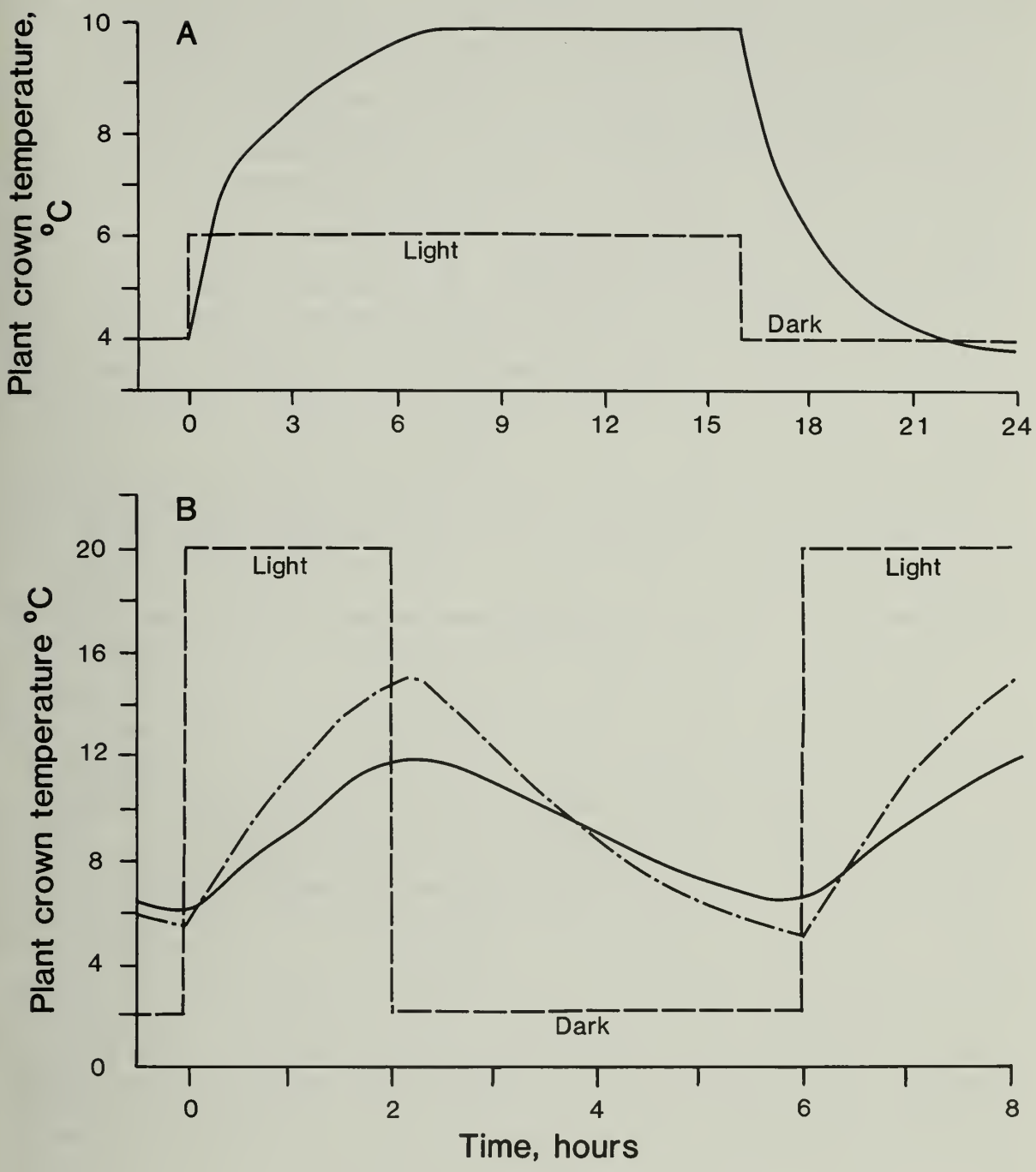


Figure 3. Plant crown temperatures during a complete temperature and light cycle; _ _ _ _, programmed temperature; _____, temperature of crown depth; ___ . ___ . ___ ., temperature of crown depth in flat with no plants.
A. Flats with plants growing under 24-h period with 8:16 h and 4:6°C light:dark, and 8-10 klx cool white fluorescent plus incandescent light.
B. Flats under 6-h period with 4:2 h and 2:20°C, and 27 klx cool white fluorescent plus incandescent light.

In studies on days to head of wheat grown at a constant 20°C under 16 hours of 21.5 klx of cool white fluorescent plus incandescent light, growth response problems have not been observed although similar types of temperature discrepancies occur. For example, in pots (1 gallon black plastic, diameter 15 cm, height 17.5 cm filled with soil) exposed to 20°C with no plants, the day temperature at 2.5 cm depth in soil was 23°C and the night temperature was 20°C. The changes in temperature under these conditions occurred over about a 2-hour period. In comparable pots with a good plant growth, the day and night temperatures were 21 and 20°C respectively. An exposed (i.e., not shielded) thermocouple in the plant canopy recorded 23°C in the light cycle and 20°C in the dark. The change from light to dark values occurred in a few minutes. If the pot was watered with tempered water (water at the temperature of the cabinet) in such a way that all water was applied directly to the soil surface, the temperature in the plant canopy changed little (ca. 1°C). If, however, the tempered water was sprinkled over the plant canopy, the temperature (exposed thermocouple) in the plant canopy fell from 23 to 20°C. The drop occurred over about 1.5 hours and had not recovered to 22°C until about 2 to 2.5 hours later. This behavior is the result of evaporative cooling induced by moisture on the thermocouple or the nearby leaves. Although we realize that exposed thermocouples should not be used to measure temperatures in high levels of light, nevertheless the plant leaves are exposed and radiant heating is one of the factors affecting leaf temperature. Further, we should realize that a plant leaf will respond to the leaf temperature rather than to the air temperature.

For a plant such as wheat, which possesses an underground growing point for several (spring types) to many (unvernalized winter types) weeks, the interpretation of experiments using large daily temperature changes is difficult. Figure 3B provides actual temperature data from crown depth in a flat of vermiculite with no plants and a flat with plants from an experiment in which a 6-hour temperature and light cycle was used. Under these circumstances, the daily temperature range is smaller under a plant canopy than in a flat without plants and the maximum and minimum temperatures are 6 and 8°C lower and approximately 4°C higher than the maximum and minimum air temperatures, respectively. Discrepancies between maximum and minimum air and crown-level temperatures were less when the length of the cycle was increased to provide 16 hours at 20°C (light) and 8 hours at 2°C (dark). The rate of rise and fall of the temperature at crown level after a change in air temperature was found to be greater in a relatively dry flat (2 days after watering in a flat with good plant growth) than in a relatively wet flat (shortly after watering in a flat with good plant growth). This effect was not noticed within 2 days in a flat of vermiculite with no plant growth.

It is assumed that water loss from a flat with good plant growth is much greater than that from a flat with no plant growth. Thus, the plant population in a container controls water levels in the medium and consequently the exact pattern of daily cycling of crown level temperatures.

LIGHT The irradiance over the growth area of a growth cabinet is not as uniform as the air temperature. In the corners it may be only 80% of that near the center. The consequences of this may not be serious at lower light intensities or normal (ca. 20°C) air temperatures. However, at higher light intensities and low (1 to 10°C) air temperatures, the lower light levels will result in lower effective temperatures (i.e., temperatures experienced by the plant). Differences in growth rate and morphology may be apparent.

Increases in the day length may cause changes in growth rates of plants which are doubtless the result of changes in the effective temperatures. For example, wheat sown and grown at 2°C under continuous 16.1 klx of cool white plus incandescent light emerged in 11 to 12 days, whereas when the air temperature was 3°C and only 16 hours per day of comparable light was provided, emergence took 4 to 5 weeks. With an 8-hour day at 3.2 klx at 3°C, emergence occurred after 6 weeks.

HUMIDITY For most of the research in growth cabinets at Lethbridge we have not found humidity control to be necessary. When higher humidities have been needed, they have been obtained by keeping water in the tray in the floor of the cabinet.

However, for studies on water relations humidity control is essential. If work on water content and cold hardiness is to be undertaken, special difficulties will be encountered since dew points below freezing will probably be needed.

AIR MOVEMENT Air movement has been reported to be a determinant of plant growth but it has been little studied under controlled conditions.

Air movement will influence leaf temperature by increasing transpiration and consequently evaporative cooling. Air movement will also increase the availability of carbon dioxide by preventing air stagnation around the leaves.

Except for their effect on temperature, responses to small changes in air movement seem to be quite small. However, under cold hardening conditions (2 to 3°C with light), growth differences on two sides of a growth cabinet with upward air flow have been observed. These have been traced to differences in air flow on the two sides of the cabinet caused by small differences in fan speeds between the two fans serving the sides of the cabinet. Such problems have not been encountered with plants growing at 20 to 25°C.

WATERING An adequate water supply is essential for plant growth. Controlling the supply of water presents serious difficulties and the available methods are limited because of the peculiarities of water movement within soils and other plant support media.

The most satisfactory method of supplying water is to use a solution culture (hydroponics). This technique requires that the roots be immersed in a very dilute solution of mineral salts (see Fig. 4). For many but not all plant species, the solution must be aerated by bubbling air through it to supply sufficient oxygen for healthy root development. The water lost by transpiration has to be replaced, as do the mineral salts taken up by the plant. This can be done manually by changing the nutrient solution at frequent intervals (frequency increasing as the plants grow) or by an automated system that replaces both water and salts taken up by the plants. Automated systems require frequent monitoring to ensure that no malfunctions have occurred.

Sand or gravel culture methods are also satisfactory if the system is carefully designed and operated. Watering with nutrient solution can be done from above or below. Watering from above is usually more satisfactory in growth cabinets. It is accomplished by allowing nutrient to drip on to the upper surface of the medium from tubing (plastic preferred) with regularly spaced small holes. Large-bore tubing, careful levelling of the system, and careful checking of hydrostatic pressures and flow rates are needed to ensure uniform watering. Flow rates must be great enough to prevent excessive salt accumulation in the medium as this will injure the plants. Facilities for drainage are necessary. Watering from below is achieved by periodically pumping nutrient up through an opening into the bottom of the container and allowing it to drain out. An overflow must be provided to control the maximum depth of nutrient in the container in each cycle. Large-bore tubing must be used and the system carefully checked to ensure that rate of nutrient flow into and drainage out of each container are similar. If this is not done, watering and growth will not be uniform from one container to another. Both systems of sand or gravel culture may be partially or completely automated. They should be monitored frequently and regularly to check for proper operation. For work between 0 and 15°C and at high temperatures above 30°C, tempered nutrient should be used to avoid the root and crown temperature effects described elsewhere.

Where levels of precision are satisfactory, manual watering with nutrient from a hose or watering can may be used.

If careful control of plant nutrition is not necessary, plants may be grown in fertile soil and watered with tap water from a hose. Tempered tap water is preferable, especially in areas where the tap water may be cold (below 10°C) for part of the year.

Studies on the responses of plants to prolonged water shortages when grown in soil present special problems which arise from the behavior of the soil water system.

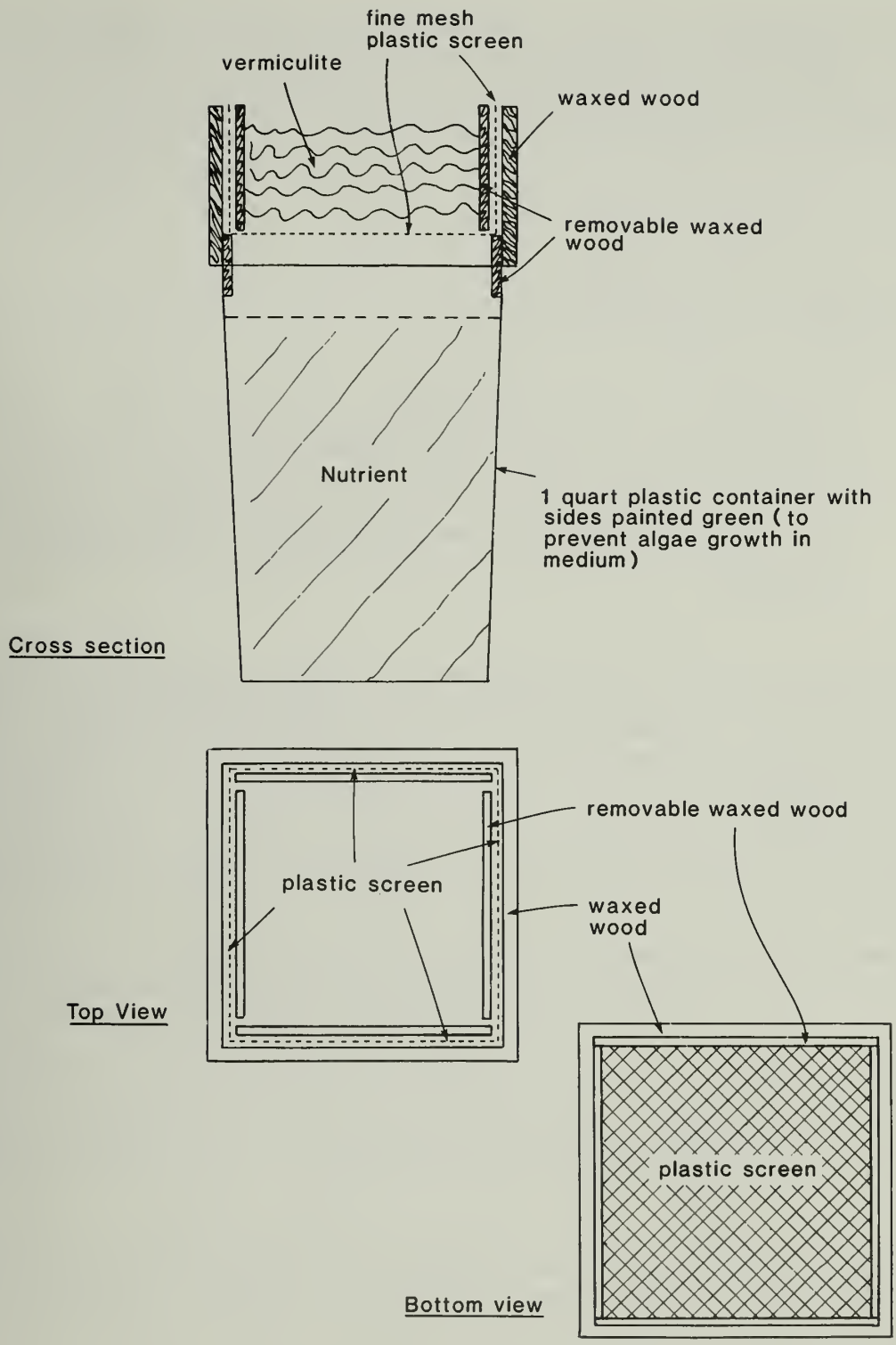


Figure 4. Containers used for solution culture of cereals at Lethbridge.

Two rather imprecise terms, field capacity and permanent wilting point, are often used by plant physiologists to describe the water status of a soil. At field capacity (water potential usually above 30 kPa) the soil contains the maximum water content possible without drainage of water occurring from it under the force of gravity. At the permanent wilting point (usually -1000 to -2000 kPa) plants will wilt and remain wilted even when transpiration ceases. Both these "constants" are affected by soil type and the latter is affected, in part, by the test species of plant that is used.

In addition to water vapor, water in the soil exists in the following intergrading categories:

(1) adsorbed on soil particles; this form requires large forces to move it,
(2) held by surface tension in the capillary pores in the soil,
(3) free water in the large pores. The latter is the only category that moves under the influence of gravity alone. When all large pores are full of water, the oxygen supply to the roots is very poor and only plants adapted to such conditions will grow properly.

Except in soils completely saturated with water, water movement in soil is chiefly along a water potential gradient (i.e., gravitational forces are unimportant). In the field, the chief force drawing water down to lower levels is derived from the low water potential of the drier soils at those levels. In the bottom of a well watered pot with drainage holes, such lower levels of dry soil do not exist, so the water potential at the drainage holes is near 0 kPa and water tends to accumulate in the bottom of a pot and slowly drain out under the influence of gravity. This results in a waterlogged layer in the bottom of a well watered pot or flat.

When dry soil is moistened with water, the water is adsorbed on the soil particles and the capillary pores fill with water before there is any free water that can move readily in the soil. This means that when soil is watered the water content must rise to field capacity before much water movement occurs. So, in a pot being watered there is a sharply defined front between the dry and wet soil (at field capacity). It is therefore not possible to water a pot full of uniformly packed soil and end up with a pot full of uniformly wet soil with a water content below that of field capacity. When a pot of uniformly dry soil is watered, the end result is either a pot full of soil at field capacity or a pot with an upper layer of soil at field capacity and a lower layer of dry soil. If the soil in the pot is caked or crusted, free water may flow to lower soil layers down cracks or down the inside of the sides of the pot.

The usual way of controlling water in plants grown in soil for studies of drought tolerance is to water the pots to field capacity, weigh the pots, and add water as soon as the water content falls to a certain predetermined level. This produces an environment with a fluctuating water supply to the plant.

In a pot with growing plants the situation is somewhat different. Roots, which are usually not uniformly distributed, can lower the water potential in the soil to the permanent wilting point. Thus, roots tend to produce a region of dryish soil (between the permanent wilting point and field capacity) around them. Adequate watering raises the moisture content back up to field capacity.

CONTAINERS Container size, shape, and color should be standardized. Container size can influence the required frequency of fertilization if soil is used as a growth medium. As the nutrient supply in small containers will be depleted sooner than in large containers, symptoms of mineral deficiencies will appear sooner in small containers. The color of the containers may affect soil temperatures as a result of the container's ability to absorb light energy during the light cycle. Clay pots can produce two side effects. The clay walls adsorb nutrients and later release them by processes similar to those exhibited by soil particles. The walls of clay pots are porous so that moisture from the soil diffuses through them and evaporates from the surface. This will cool the pot and its contents. Container geometry can affect the temperature of the medium as discussed in the section under temperature.

NUTRITION AND MEDIA Ten elements (macronutrients) are required in moderate to large amounts for plant growth. Water supplies hydrogen and oxygen. Carbon dioxide in the air supplies the carbon. The others--calcium, magnesium, nitrogen, phosphorus, potassium, sulfur, and iron--are supplied by the soil. In addition, six elements (boron, chlorine, copper, manganese, molybdenum, and zinc) are required in trace quantities (micronutrients). Halophytes require sodium. Cobalt is required for the symbiotic fixation of nitrogen by legumes. Excessive quantities of the micronutrients and most macronutrients can be toxic. If nutrients are supplied to sand or gravel culture containers from above, either from watering cans or by drip irrigation, care must be taken to supply sufficient nutrient to flush excess salts from the medium or salts will build up and may become toxic.

The nutrient solution most often used at Lethbridge is a modification of Hoagland's No. 1 (see Appendix 13) with the iron supplied as iron citrate. Because use of ferrous sulphate resulted in iron deficiency symptoms in wheat, iron citrate recommended by Hewitt (1952) was used instead. It is satisfactory but troublesome to dissolve.

Three growth media are used at Lethbridge. These are soil, Cornell mix (see Appendix 12), and vermiculite. The history of the soil in use at Lethbridge Research Station has been known since 1906. It was obtained from the headland of one of the Research Station experimental areas when a road was widened. No pesticides or fertilizers had been used on the land and it had been sown to grass for many years. The soil was collected several years ago and is expected to last another 15 to 20 years.

When it was available, a fine (No. 5 or plaster aggregate) grade of vermiculite was the most satisfactory. No. 3 or medium grade vermiculite is now being used. Seed is sown directly into dry vermiculite. As a precaution, we find it necessary to wash the vermiculite thoroughly with distilled water when the seed is moistened. This serves to flush out some unidentified water-soluble toxin that has been found occasionally in the vermiculite we use. The toxin prevents seed germination and results in wheat plants with short dark green leaves.

CARBON DIOXIDE Carbon dioxide is the substrate for photosynthesis and by far the most important carbon source for green plants. It is frequently the limiting factor that controls the rate of photosynthesis. Two other potentially limiting factors are light and temperature. When carbon dioxide levels fall to low limiting values they control the rate of photosynthesis, and increases in light and or temperature will have little or no effect on the rate of photosynthesis. Because of their effect on the rate of photosynthesis, changes in CO_2 levels will affect growth rate. There are reports in the literature suggesting that CO_2 may have additional biochemical and morphological effects on plant growth (Strain 1978).

Carbon dioxide levels in the atmosphere have been gradually rising. It is believed they were around 275 ppm before the industrial revolution. By 1900 they had risen to approximately 290 ppm, by 1960 to 320 ppm, and by 1976 to close to 330 ppm. They are thought to be increasing at around 0.7 ppm per year at present. They tend to rise in winter and fall in summer due to photosynthetic uptake by plants. The annual range is around 6 ppm.

Human activity affects local CO_2 levels. Levels are high in large cities with lots of human activity and oxidation of fossil fuels and low in the rural areas, especially in summer. In houses and office buildings they rise to 600 ppm. Levels of carbon dioxide above 2% may cause toxic symptoms in plants if they persist for long periods of time.

In a sealed growth cabinet, CO_2 levels will fall rapidly during the light cycle. C-4 plants like corn can lower CO_2 levels in the light cycle to 50 ppm and C-3 plants like cotton can produce CO_2 levels up to 150 ppm. The presence of an investigator in a walk-in growth room may raise the CO_2 levels to between 500 and 600 ppm. During the dark cycle, CO_2 levels will rise due to plant respiration.

Prevention of large changes in CO_2 concentration will require impractically great rates of air exchange between outdoor air and growth chamber air. Such exchanges are theoretically calculated to be as high as 75% of chamber volume per minute. Exchange with ambient air may cause problems if there is much human activity in the room surrounding the plant growth room (high CO_2) or if there are many plant growth chambers in the vicinity (low CO_2 if all lights are on at the same time).

Commercial plant growth cabinets have provision for exchange of outside air. Such provision, however, falls short of that required to maintain CO_2 levels in a cabinet full of large, rapidly growing plants. To some extent this is compensated for by the fact that most commercial cabinets are not very air-tight, a fact attested to by the problems of maintaining low humidities inside them.

Controlled additions of CO_2 (free from compressor oils) to the growth cabinet atmosphere are the best way to control CO_2 levels in the light cycle. Removal of excess CO_2 during the dark cycle poses greater problems and there is not universal agreement on a satisfactory method for achieving this.

Control of CO_2 levels requires monitoring. The most accurate method of determining CO_2 is with an infra red gas analyzer. This equipment is expensive and requires careful operation if accurate data are to be obtained. A cheaper system is based on the fact that, as CO_2 concentration in distilled water increases, so does electrical conductivity. The air to be analyzed is bubbled through water which is then passed through a conductivity cell. Both of these methods may be connected to an automated system for additive control of CO_2 levels.

OTHER GASES The control of oxygen levels is not normally required in growth cabinets studies, even though modified levels are used commercially for fruit storage and ripening.

Sealed growth cabinets may be used for study of air pollutants. With such units it must be remembered that plants, especially those with ripening fruits, give off ethylene, a plant growth regulator causing epinasty and accelerating leaf fall and fruit ripening. With very sensitive plants it may be necessary to filter the ventilating air to remove air pollutants. The topic of pollutants is not under investigation at Lethbridge and its detailed discussion is outside the scope of this bulletin.

DISEASES AND PESTS The discussion of diseases and pests will be confined to those diseases and pests which are or have been a problem in the Phytotron and greenhouse at Lethbridge. The problems are to some extent determined by the crops that are grown and by the diseases and pests prevalent in the outdoors.

The most important aspect of disease and pest control is prevention. In practice, this means sanitation. Sanitation is the biggest problem in greenhouses.

Normal growth cabinet operation usually involves completely removing one crop before the next one is planted. If the cabinet is left empty for a week or two, or if a very high temperature is maintained for a shorter period of time, the pests will be eliminated. Leaving the cabinet empty allows time for preventive maintenance of the refrigeration equipment and permits thorough cleaning. The first step in cleaning is to remove all

plants and plant debris, followed by sweeping and vacuuming. Then the growth cabinet floors are removed and soaked overnight in "Lime-a-way" (a commercial descaling preparation with phosphoric acid as the active ingredient), and later rinsed with water. The tray under the floor is vacuumed and rinsed. If the tray is heavily crusted with salts, Lime-a-way is used to remove all scale and dirt. Finally, if necessary, the cabinet walls are washed with soap or detergent.

Care is taken to avoid introducing diseased or insect-infested plants into the clean cabinets. Since we have a large operation, greenhouse staff on weekdays can be assigned to look after specific areas. This reduces the chances of a pest or disease moving from one area to another (e.g., from greenhouses to growth cabinets) on staff clothing or bodies. Cabinet doors are kept closed as much as possible since many of the problems enter through the doors and spread out from the areas around the doors.

Greenhouse sanitation is a much greater problem largely because there is such a temptation not to clean out all the plants from a greenhouse compartment or room at one time. Even a few plants under the benches can harbor small residual populations of the more troublesome pests. For best results, expanded metal rather than wooden bench tops are used. Gravel floors have been replaced with concrete. Both these changes have reduced our pest problems. Between experiments, all plants and plant debris are removed from a greenhouse compartment or room. The floors, including all corners and areas under the benches, and the metal tops are flamed with a propane weed burner if there has been a pest or disease problem and usually a very high temperature is maintained for two or three days to eliminate the pests.

Most greenhouse pests come in from outdoors. The entry of some of these can be prevented by screening the openings. Air introduced in the summer through the swamp coolers is filtered of pests that might enter with the incoming air. The positive pressure built up in the greenhouse also helps prevent the entry of diseases and pests.

Powdery mildew (*Erysiphe* sp.) is a problem on cereals and some other crops in the greenhouse and growth cabinets. It produces small, white, powdery lesions on the leaves and stems. It tends to be more serious under conditions of low light in the winter in the greenhouses. Spread is rapid. Problems in growth cabinets develop on older plants, probably because the growth cabinets are cleaned before seeding and it takes time before the disease is introduced into the cabinet. It is uncommon on cereals under hardening conditions, probably because of the low temperature. Spraying with Bayleton is the best method of control in a growth cabinet. Fine sulfur dusted over the plants works well in a greenhouse, but sulfur is too corrosive for regular use in a growth cabinet.

Damping off (caused by one or more of several fungi including *Pythium, Rhizoctonia, Fusarium, and Phytophthora* spp.) is sometimes a problem, especially when seeds are planted deep. It does occur in the greenhouse. Where *Pythium* is the chief problem, proper watering is

important. Plants must not be allowed to dry out too much nor should they be overwatered. Captan or other seed dressings can be used as a fungicide for partial control. Soil sterilization is sometimes recommended but a sterile soil is an excellent medium for growth of fungi that cause root diseases because sterilization removes competing organisms.

Rusts have not been a problem because the climate of the Lethbridge area is too dry for a rapid buildup in most years.

Healthy seed is used to reduce seed-borne diseases.

In general, the use of persistent systemic insecticides and miticides is avoided for control of pests. Some of these systemics are quite toxic to humans, a property shared with many other insecticides and miticides. In an institution like ours, where entomological research is carried out, care must be taken, especially with persistent systemics, to avoid contamination of the phytotron and greenhouses since some scientists use these facilities for studying insects.

The greenhouse staff have been trained in using pesticides. They wear proper protective clothing when applying pesticides. Treated areas are sealed off as far as possible and posted with necessary warning signs.

The two-spotted spider mite, *Tetranychus urticae*, is a serious problem. Mites usually feed on the underside of leaves by sucking the plant juices. They produce small, pale-colored spots lacking the tiny black spots characteristic of thrip damage on leaves. They may be seen and identified with a magnifying glass since they have eight legs, whereas adult insects have only six legs. In a growth cabinet, they are controlled by spraying with Pentac, Kelthane E, Morestan, and Vendex 50 W. In the greenhouse, fumigation with Plantfume 103, DDVP, or Tedion is satisfactory. These compounds are too toxic to humans for use in a growth cabinet or growth room.

Various species of aphids are a problem because they suck plant juices, may transmit virus diseases, or inject toxins into plants. Aphids have six legs and are usually present in a wingless form. However, most species have at least one winged form in their life cycle. Fumigation with nicotine is effective in the greenhouse. In a growth cabinet or growth room, one or two sprayings with Pirimor is sufficient for control in a cereal, canola (rape), or safflower crop.

Thrips are tiny insects that suck plant juices. Their presence is indicated by small pale spots on the leaves. The spots are associated with tiny black dots (feces) which help differentiate thrip infestations from mite infestations. Fumigation with nicotine or Plant Fume 103 gives good control in the greenhouse. Spraying with orthene works in the growth rooms and growth cabinets.

Whitefly, *Trialeurodes vaporariorum*, used to be a problem in the greenhouse, especially on beans. They have not been a problem in growth chambers and growth rooms. With the introduction of all the sanitation methods described above, whiteflies have been largely eliminated from the greenhouses. They may be controlled by spraying with Ambush.

Mealybugs also were a problem. They are flattened oval insects, usually without wings, 3 to 7 mm long and covered with a white powdery wax. They have been eliminated from our greenhouses by sanitation procedures.

Fungus gnats or manure flies (*Platyura* sp. and *Sciara* sp.) occur occasionally and are controlled by malathion drenches.

Algae can cause problems. They will grow in the nutrient solutions used for watering. Such solutions must be kept in the dark or covered with green garbage bags to exclude the light. Although they grow on the surface of media at cold hardening temperatures (i.e., 0 to 10°C), they have not caused problems. Sanitation of cabinets prevents serious buildups.

Mice are a recurring problem, mostly in the greenhouses. We also have had them in the controlled temperature rooms at 25°C when seed was being stored for conditioning in the room. They often appear in the fall in the greenhouses. They dig up and eat newly planted sprouting seeds, eat ripe and ripening seeds on the plants, and chew off the heads of wheat. All seed should be stored in mouseproof containers. Mice are best eliminated by trapping. Flats with germinating seeds may be protected by supporting them on glazed crocks. Such flats must be well away from walls and other objects up which the mice can climb and from which they can jump onto the flat. Metal screening may also be used to cover the flats.

MANAGEMENT OF FACILITIES

The Phytotron Committee sets the policies for the operation of the Phytotron. The chairman of the Phytotron Committee is employed full-time as a scientist but manages the Phytotron and allocates facilities. The maintenance supervisor is responsible for all maintenance and keeps all maintenance records. The programmer is responsible for programming all facilities and for modifying programs, for minor maintenance, and for replacing and ordering lamps. The greenhouse supervisor is responsible for the watering of all plants, preparing pots and soil for seeding, for discarding soil and plants from completed experiments, and for keeping the Phytotron facilities and the Phytotron area clean and free of mites, insects, mice, and diseases.

Each scientist is responsible for completing a Phytotron Program form (see Appendix No. 5) with the following information: the facility required, the project number and short title, the crop grown, the scientist's name and office and home phone numbers, the technician's or associate's name and office and home phone numbers, the date the facility is required, the estimated time for completion of the experiment, the date the facility was requested, the scientist's signature, lighting, temperature, humidity, and watering instructions, and any special instructions.

Any changes to the program must be in writing on the Shut Down and Program Change Request form (Appendix 7). The scientist's and technician's names and phone numbers are required so that they can be phoned if there is a problem with the growth facility and instructions are needed concerning the experiment.

Scientists are expected to check lights, temperature, and humidity of the Phytotron unit they are using throughout the experiment to make sure that the conditions are exactly what they requested. The scientist is responsible for seeding all pots and for making all observations and records of the experiment.

Each scientist is responsible for filling out a Phytotron Work Order form (see Appendix 6) indicating the number, size, and type of pots required, the soil mixture or media needed, the type of watering (tap water, distilled water or a specific nutrient solution), and the greenhouse or plant growth unit in which the pots or flats are to be placed.

When the experiment has been completed, the scientist fills in the Shut Down and Program Change Request form (Appendix 7) and informs the greenhouse supervisor of how the material should be disposed. Plants infested with insects, infected with disease, or treated with pesticides are placed in plastic bags and disposed of in a sanitary landfill, while healthy plants and untreated soil are placed in a compost pile.

All our facilities have routine maintenance at least twice a year (see Preventative Maintenance form, Appendix 8). After each experiment the unit is thoroughly cleaned and washed prior to the maintenance inspection. Three times each week all lights in the phytotron are inspected and burnt-out bulbs or ballasts are replaced. A record is kept by the maintenance supervisor of all repairs to each plant growth unit.

GUIDELINES FOR REPORTING PHYTOTRON EXPERIMENTS

Plant growth facilities differ in design, maintenance, air flow patterns, and other factors which may affect experimental results. Complete and accurate interpretation of experimental results is difficult or almost impossible if the environment in the plant growth facility is not adequately reported. Guidelines for measuring and reporting environmental factors in controlled environment facilities have been published by Spomer (1980, 1981) and Sager (1982). Our experience suggests the following guidelines.

The guidelines are divided into two categories, those which ought to be reported (essential) and those which ideally should be reported (desirable). It must be recognized that the measuring equipment and available staff will influence which of the additional conditions will be measured. However, the preceding discussion of environmental conditions should be used as a guide to which of the ideally measured conditions are likely to be important. Every effort should be made to measure these, and all that deviate greatly from naive expectations ought to be reported. These measurements become more important as growing conditions deviate from 20 to 25°C, as light intensity becomes high, and as daily air temperatures are varied by more than a few degrees C.

Equipment

Make and model number of the cabinet or room.

Temperature (°C)

ESSENTIAL

1. Air temperature with a shielded sensor. Specify whether constant or variable. If variable, give day and night temperatures and specify nominal rate of change from day to night conditions.

2. If substrate temperature was controlled separately (as in soil temperature tanks or with heaters or refrigeration coils), provide set or nominal values and a summary of measured values. Note that if it was important enough to provide separate temperature control for substrate temperature, then values ought to be measured and reported for light and dark periods of the daily cycle.

DESIRABLE

1. Substrate temperature, if not controlled independently. Measure at plant crown level for species with crowns below the soil surface or at least at one shallow depth for other species. Summarize briefly the results if conditions (air temperature or light) were cycled. Check and report in summary form if crop was grown long enough to cause shading of the medium by plant canopy.

2. Leaf temperature. Measure during both the light and dark cycles for leaves exposed directly to the light and if relevant for those shaded by upper levels of the plant canopy.

3. Specify types of temperature sensors employed.

4. Tolerance limits during normal cycling of equipment.

Light

ESSENTIAL

1. Specify photoperiod and whether change from dark to light period was abrupt or gradual. If gradual, indicate how rapidly. State if photoperiod and thermoperiod coincide and if not, describe difference.

2. Types of lamps used. Provide information on type (e.g., incandescent, fluorescent, etc.), power rating and voltage applied, and phosphor for fluorescent lights.

3. Light intensity. Measure just above the plant canopy or at medium level at seeding time. Any of the three units described above may be used but make and model of meter employed should be stated. When two light sources were used (e.g., incandescent and cool white fluorescent) give data separately for each light source.

DESIRABLE

1. Tolerance limits for light intensity. State limits over area of plant growth at a specified level. State frequency of monitoring of light intensity and deviation from nominal values permitted.

2. Graph of spectral energy distribution at start of experiment. State if this was monitored subsequently and what changes occurred.

Relative humidity

ESSENTIAL

1. Provide day and night values. Describe type of sensor and controlling mechanism.

DESIRABLE

1. Provide tolerance levels.

2. Outline any variations associated with daily cycling of the cabinet (including those associated with watering) with development of the crop or in the crop canopy.

Carbon dioxide

ESSENTIAL

1. State how CO_2 levels were controlled.

DESIRABLE

1. Provide data on daily cycling of CO_2 levels for a designated location in or near the plant canopy. Specify measuring device used.

Air movement

DESIRABLE

1. Indicate if air flow was up, down or horizontal. Specify how and where this was measured and provide data.

Containers, media, and nutrients

Note: Literature references should be used where appropriate. In the absence of such references, all details outlined below should be provided.

ESSENTIAL

1. Containers. State type of container (wood, plastic, glass, clay), color, and inside dimensions. If a hydroponic system was used, provide details of construction including information on monitoring tests used to ensure proper operation.

2. Substrate. Include information on amendments and added fertilizer.

3. State how water and nutrients were supplied (e.g., hose, watering can, manual hydroponic system, automated hydroponic system, etc.).

4. Nutrient solutions. If a literature reference cannot be supplied, then a complete list of ingredients including concentrations must be provided. Frequency of changes of nutrient solution, frequency and composition of additions to the nutrient solution, and monitoring techniques should be stated where applicable.

DESIRABLE

1. If nutrient or water was added manually from a hose or watering can, temperature and frequency of added water or nutrient should be specified. Indicate quantities applied. State if water or nutrient was added directly to the surface of the medium or sprinkled on the plant canopy. Monitor substrate and canopy temperature changes associated with watering and describe these.

REFERENCES AND SUPPLEMENTARY READING

Althouse, A. D., Turnquist, C. H. and Bracciano, A. F. 1975. Modern refrigeration and airconditioning. Goodheart-Willcox Co. Inc., South Holland, Illinois. 988 pp.

Anderson, J. M. 1986. Photoregulation of the composition, function, and structure of thylakoid membranes. *Ann. Rev. Plant Physiol.* 37: 93-136.

Berry, J. and Bjorkman, O. 1980. Photosynthetic response and adaptation to temperature in higher plants. *Ann. Rev. Plant Physiol.* 31: 491-543.

Bickford, E. D. and Dunn, S. 1972. Lighting for plant growth. Kent State Univ. Press, Kent, Ohio. 221 pp.

Blackman, F. F. 1905. Optima and limiting factors. *Ann. Bot.* 19: 281-295.

Boodley, J. W. and Sheldrake, R. Jr. 1977. Cornell peat-lite mixes for commercial plant growing. New York State College of Agric. and Life Sciences. Inf. Bull. No. 43. Cornell University, Ithaca, New York.

Clayton, R. K. 1970. Light and living matter. Vol. 1. The physical part. McGraw-Hill, New York.

Downs, R. J. 1975. Controlled environments for plant research. Columbia Univ. Press, New York. 175 pp.

Downs, R. J. 1980. Phytotrons. *Bot. Rev.* 46: 447-489.

Downs, R. J. and Bailey, W. A. 1967. Control of illumination for plant growth. Pp. 635-645 *in* Wilt, F. H., Wessles, N. K. (eds.). Methods in development biology. Thomas Crowell, New York.

Downs, R. J. and Banaminio, V. P. 1976. Phytotron procedural manual for controlled-environmental research at the Southeastern Plant Environment Laboratories. North Carolina Agric. Expt. Sta. Tech. Bull. No. 244. 36 pp.

Downs, R. J. and Hellmers, H. 1975. Environment and the experimental control of plant growth. Academic Press, New York. 145 pp.

Epstein, E. 1972. Mineral nutrition of plants: principles and perspectives. John Wiley, New York. 412 pp.

Evans, L. T. (ed.) 1963. Environmental control of plant growth. Academic Press, New York. 449 pp.

Federer, C. A. and Tanner, C. B. 1966. Sensors for measuring light available for photosynthesis. *Ecology* 47: 654-657.

Gauch, H. G. 1972. Inorganic plant nutrition. Dowden, Hutchinson and Ross, Stroudsburg, Pennsylvania. 488 pp.

Grace, B. and Hobbs, E. H. 1986. The climate of the Lethbridge agricultural area: 1902-1985. Lethbridge Research Station Mimeo Rept. 3 (revised). 39 pp.

Hatch, M. D., Osmond, C. B. and Slayter, R. O. 1971. Photosynthesis and photorespiration. Proceedings of a conference held at Australian National University, Canberra, Australia, Nov. 23-Dec 5, 1970. Wiley Interscience, New York. 565 pp.

Heck, W. W. 1972. Air pollution research on plants in phytotrons. NSF-UNESCO-SEPEL Symposium, Durham, North Carolina.

Hellmers, H. and Hesketh, J. D. 1974. Phytotronics and modelling plant growth. Pp. 637-644 *in* Mechanisms of regulation of plant growth. Royal Society of New Zealand, Wellington, New Zealand.

Hewitt, E. J. 1952. Sand and water culture methods used in the study of plant nutrition. Commonwealth Bur. Hort. and Plantation Crops. East Malling, Maidstone, Kent. Tech. Comm. No. 22. Commonwealth Agricultural Bureau. 241 pp.

Hoagland, D. R. 1948. Lectures on the inorganic nutrition of plants. Chronica Botanica. Waltham, Massachusetts. 226 pp.

Hoagland, D. R. and Arnon, D. I. 1950. The water-culture method for growing plants without soil. California Agric. Expt. Sta. Circular No. 347. 32 pp.

Hudson, J. P. 1957. Control of plant environment. Butterworths, London. 240 pp.

Kozlowski, T. T. (ed.) 1976. Water deficits and plant growth IV. Academic Press, New York. 383 pp.

Kramer, P. J. 1949. Plant and soil water relationships. McGraw Hill, New York.

Lange, O. L., Nobel, P. S., Osmond, C. B., Ziegler, H. (eds.) 1981. Physiological plant ecology. I. Responses to the physical environment. Encyclopedia of Plant Physiology. Vol. 12A. Springer-Verlag, New York.

Langhams, R. W. 1978. A growth chamber manual. Comstock Publishing Co., New York. 222 pp.

Levitt, J. 1972. Responses of plants to environmental stresses. Academic Press, New York. 697 pp.

LI-COR Inc. 1979. Instrumentation for biological and environmental sciences. LI-COR Inc./LI-COR Ltd., Lincoln, Nebraska. 49 pp. (Excerpted from: Advanced Agricultural Instrumentation. Proc. NATO Advanced Study Institute on Advanced Agricultural Instrumentation. W. G. Gensler, ed. Martinus Nijhoff Publishers, Dordrecht, The Netherlands.)

Matsumura, S. (ed.) 1982. Environment-controlled growth rooms in Japan. Committee for environment-controlled growth rooms. Faculty of Agriculture, University of Tokyo, Tokyo. 67 pp.

McCree, K. J. 1981. Photosynthetically active radiation. *In* Lange, O. L., Nobel, P. S., Osmond, C. B., Ziegler, H. (eds.) 1981. Physiological plant ecology. I. Responses to the physical environment. Encyclopedia of Plant Physiology. Vol. 12A. Springer-Verlag, New York.

Miyayama,H., Funada, S., Kato, M., Konishi, M., Matsui, T., Miyagawa, H., Terajima, T., and Yamaki, T. (eds.) 1972. Phytotrons and growth cabinets in Japan. Japanese Soc. Environment Control in Biology. Faculty of Agric., Kyoto University. 93 pp.

Morse, R. N. 1963. Phytotron design criteria - engineering considerations. Pp. 20-37 *in* Engineering aspects of environment control for plant growth. CSIRO, Melbourne, Australia.

Peacock, J. M. 1975. Temperature and leaf growth in *Lolium perenne*. II. The site of temperature perception. *J. Appl. Ecol.* 12: 115-123.

Platt, R. B. and Griffiths, J. F. 1964. Environmental measurement and interpretation. Reinhold, New York. 235 pp.

Rees, A. R., Cockshull, K. E., Hand, D. W. and Hurd, R. G. (eds.) 1972. Crop processes in controlled environments. International Symposium held at the Glasshouse Crops Research Institute, Little Hampton, Sussex, England. July, 1971. Academic Press, New York.

Sager, J. C. 1982. Guidelines for measuring and reporting environmental parameters for plant experiments in growth chambers. Paper 82-4056. Summer Meeting Amer. Soc. Agric. Engineers, St. Joseph, Michigan. U. of Wisconsin-Madison. June 27-30, 1982.

Seliger, H. H. and McElroy, W. D. 1965. Light: Physical and biological action. Academic Press, New York.

Shropshire, W. Jr. and Mohr, H. (eds.) 1983. Photomorphogenesis. Encyclopidia of plant physiology. Vols. 16A and 16B. Springer-Verlag, New York. 832 pp.

Slayter, R. O. 1967. Plant-water relationships. Academic Press, London and New York. 366 pp.

Spomer, L. A. 1980. Guidelines for measuring and reporting environmental factors in controlled environment facilities. *Commun. Soil Sci. Plant Anal.* 11: 1203-1208.

Spomer, L. A. 1981. Guidelines for measuring and reporting environmental factors in growth chambers. *Agron. J.* 73: 376-378.

Strain, B. R. (ed.) 1978. Report of the workshop on anticipated plant responses to global carbon dioxide enrichment. Duke Environmental Centre, Duke University, Durham, North Carolina.

Tibbitts, T. and Kozlowski, T. K. (eds.) 1979. Controlled environment guidelines for plant research. Academic Press, New York. 413 pp.

Tobin, E. M. and Silverthorne, J. 1985. Light regulation of gene expression in higher plants. *Ann. Rev. Plant Physiol.* 36: 569-593.

Weast, R. C., Astle, M. J. and Beyer, W. H. (eds.) 1985-86. CRC handbook of chemistry and physics. 66 edition. CRC Press. Boca Raton, Florida. p. E-41.

Went, F. W. 1957. The experimental control of plant growth. Chronica Botanica, Waltham, Mass. 343 pp.

Zelitch, I. 1971. Photosynthesis, photorespiration and plant productivity. Academic Press, New York and London. 347 pp.

APPENDIX 1

Summary of responsibilities

General responsibility for Phytotron	Chairman, Phytotron Committee
Completing phytotron request form	Scientist or technician
Space allocation	Chairman, Phytotron Committee
Programming facilities	Phytotron staff
Filling pots and watering	Phytotron staff
Seeding	Scientist or technician
Special soil or seed treatments	Scientist or technician
Discarding pots and plants	Phytotron staff
Mechanical adjustments	Phytotron staff
Changing lights	Phytotron staff
Repair and maintenance	Maintenance supervisor
General surveillance of experiment	Scientist or technician
Monitoring facilities	
Day	Phytotron staff
Night	Commissionaire

APPENDIX 2

Plant growth rooms

Propagation Rooms

Room No.	Size (m)	Area (m^2)
L-026	5.13 x 10.77	55.25
L-032	5.13 x 6.71	34.42
L-036	5.13 x 6.71	34.42
L-040	5.13 x 8.97	46.02
L-041	5.52 x 3.83	21.14
L-043	5.52 x 3.83	21.14
L-045	5.11 x 3.66	18.70
L-047	5.11 x 3.66	18.70
L-048	5.11 x 8.64	44.15
L-052	5.11 x 6.71	34.29
L-058	5.11 x 6.71	34.29
L-062	5.11 x 6.71	34.29
L-066	5.11 x 4.11	21.00
SC-15	5.11 x 3.81	19.47
SC-24	5.08 x 4.22	21.44
Total		458.72

High Ceiling Rooms

SC-6	5.05 x 3.35	16.92
SC-7	5.05 x 3.35	16.92
SC-8	5.05 x 3.07	15.50
SC-9	5.05 x 3.35	16.92
Total		66.26

Soil Tank Rooms

SC-11	5.11 x 3.81	19.47
SC-12	5.11 x 3.81	19.47
SC-13	5.11 x 3.81	19.47
SC-14	5.11 x 3.81	19.47
Total		77.88
TOTAL GROWTH ROOM AREA		602.86

APPENDIX 3

Plant growth room benches

Propagation Room Benches

Room No.	No. Benches	Bench size (m)	Bench area (m^2) Each	Total
L-026	4	1.42 x 5.13	7.28	29.12
L-032	2	1.42 x 5.13	7.28	14.56
L-036	2	1.42 x 5.13	7.28	14.56
L-040	3	1.42 x 5.13	7.28	31.84
L-041	1	1.42 x 4.98	7.07	7.07
L-043	1	1.42 x 4.98	7.07	7.07
L-045	1	1.12 x 5.11	5.71	5.71
L-047	1	1.12 x 5.13	5.75	5.75
L-048	3	1.42 x 5.11	7.26	21.78
L-052	2	1.42 x 5.11	7.26	14.52
L-058	2	1.42 x 5.11	7.26	14.52
L-062	2	1.42 x 5.11	7.26	14.52
L-066	1	1.42 x 5.11	7.26	7.26
SC-15	2	1.45 x 5.05	7.32	14.64
SC-24	2	1.09 x 5.08	5.54	11.08
Total				204.00

High Ceiling Room Benches

SC-6	2	1.30 x 5.05	6.57	13.14
SC-7	2	1.30 x 5.05	6.57	13.14
SC-8	2	1.30 x 5.05	6.57	13.14
SC-9	2	1.30 x 5.05	6.57	13.14
Total				52.56

Soil Tank Room Benches

SC-11	2	1.45 x 5.05	7.32	14.64
SC-12	2	1.45 x 5 05	7.32	14.64
SC-13	2	1.45 x 5.05	7.32	14.64
SC-13	2	1.45 x 5.05	7.32	14.64
Total				58.56
TOTAL PLANT GROWTH AREA				315.12

APPENDIX 4

Experimental rooms with limited light

Room No.	Temp. (°C)	Size (m)	Area (m^2)
SC-16D	25	2.79 x 1.83	5.11
SC-16F	20	2.79 x 1.83	5.11
SC-16B	15	2.79 x 1.83	5.11
SC-16E	10	2.79 x 1.83	5.11
SC-16C	5	2.79 x 1.83	5.11
SE-14	5	3.01 x 2.01	6.13
SE-15	5	3.01 x 2.01	6.13
SE-11	5	2.44 x 1.83	4.47
SE-1	3	5.00 x 3.91	19.55
SE-16	2.5	3.01 x 2.01	6.13
SE-10	.75	2.44 x 1.91	4.66
SC-16A	.5	2.79 x 1.83	5.11
SC-17F	-3	2.79 x 1.83	5.11
SC-17E	-5	2.79 x 1.83	5.11
SC-17D	-10	2.79 x 1.83	5.11
SC-17A	-15	2.79 x 1.83	5.11
SC-17B	-20	2.79 x 1.83	5.11
SC-18A	-20	5.72 x 1.83	10.47
SC-18B	-40	3.76 x 1.68	6.32
SC-23B	-40	3.35 x 3.66	12.26
SE-2	-40	3.66 x 2.97	10.87
SC-17C	-20 to +25	2.79 x 1.83	5.11
SC-23A	-20 to +25	2.39 x 2.08	4.97

APPENDIX 5

PHYTOTRON PROGRAM FORM

COMPLETE SECTIONS: 1 - 2 - 3 - 5 [X] ALL APPROPRIATE BOXES

SECTION "1"

CABINET REQUIRED # _____ CROP _____

TITLE OF EXPERIMENT _____ PROJECT # _____

SCIENTIST: _____ ALTERNATE: _____

PHONE: _____ (OFFICE) _____ (HOME) PHONE: _____ (OFFICE) _____ (HOME)

SECTION "2" IN THE EVENT OF CABINET MALFUNCTION - AFTER 4:30 PM AND WEEKENDS

[ ] 1) NOTIFY SCIENTIST [ ] NOTIFY ALTERNATE [ ]

IF NO ONE CAN BE REACHED:

[ ] - SHUTDOWN UNTIL SCIENTIST CAN BE REACHED

[ ] - CALL MAINTENANCE STAFF IN

[ ] - SHUTDOWN TILL NEXT WORKING DAY

[ ] 2) SHUTDOWN AND CALL MAINTENANCE STAFF IMMEDIATELY

[ ] 3) SHUTDOWN UNTIL NEXT WORKING DAY

SECTION "3"

WATERING _____

NUTRIENT _____

PESTICIDE _____

OTHER _____

SECTION "4" FOR PROGRAMMER USE ONLY

1																								
2																								
3																								
TEMP. TIME	24	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24

SECTION "5" - PROGRAM INSTRUCTIONS

1) LIGHTING: FLUORESCENT COOL WHITE [ ] INCANDESCENT BULBS [ ]

FLUORESCENT GROW LUX WS [ ] NO INCANDESCENT BULBS [ ]

2) LIGHTS ON _____ AM [ ] PM [ ]

LIGHT INTENSITY 1/3 [ ] 2/3 [ ] FULL [ ]

LIGHTS ON _____ AM [ ] PM [ ]

***NOTE - ANY FURTHER LIGHTING INSTRUCTIONS LIST ON REVERSE SIDE.

3) TEMPERATURE: DAY _____ C
NIGHT _____ C

***NOTE - ANY FURTHER TEMPERATURE INSTRUCTIONS LIST ON REVERSE SIDE.

4) RELATIVE HUMIDITY: DAY _____%
NIGHT _____%

***NOTE - ANY FURTHER INSTRUCTIONS LIST ON REVERSE SIDE.

5) DATE EXPERIMENT WILL ENTER CABINET _____

*****ATTENTION: NO PROGRAMMING ONE DAY BEFORE A HOLIDAY
MINIMUM OF FIVE WORKING DAYS NOTICE FOR START-UPS, IN ADVANCE

DATE: _____ SIGNATURE: _____

APPENDIX 6

AGRICULTURE CANADA RESEARCH STATION
Lethbridge, Alberta T1J 4B1

PHYTOTRON WORK ORDER Work Order No. ☐☐☐

Date requested _____ Requested by _____
Section: AS CE PP PS SS VM ADA

Date required _____ Phone No. _____

Location: Greenhouse No. _____ GC No. _____ GR No. _____ PR No. _____
Other _____

Work required: ALLOW 7 WORKING DAYS FOR COMPLETION OF ORDER

Containers filled: Type and Size _____ Number _____

Soil Mixture (ratio): Soil _____ Sand _____ Peat Moss _____ Manure _____

Special (specify) _____

Containers emptied: No. _____ To Compost Pile _____ City Dump _____

Pest Control: Type _____ Treatment _____

_____

Other: _____

_____

(Greenhouse Use Only)

Priority _____ Date started _____ Date Completed _____

Notes _____

_____

By _____
Greenhouseman

ACKNOWLEDGEMENT

Work Order No. ☐☐☐

Requested by _____ Date order received _____

Expected completion date as requested _____ or _____

_____

_____

Date _____ By _____
Greenhouseman

APPENDIX 7

SHUT-DOWN AND PROGRAM CHANGE REQUEST UNIT #

COMPLETE ONLY THOSE SECTIONS WHICH PERTAIN TO YOUR NEEDS: ☒ ALL APPROPRIATE BOXES

SECTION "1"

SHUT-DOWN ..... ☐
CLEAN UNIT ..... ☐ DATE ACTION REQUIRED _____
I WILL NOT BE REUSING THIS CABINET ... ☐
I WILL BE USING THIS CABINET AGAIN ... ☐ DATE OF RE-USE _____

SECTION "2"

CHANGE: LIGHT INTENSITY - OFF ☐ DATE ACTION REQUIRED _____
- 1/3 ☐
- 2/3 ☐
- FULL ☐

OTHER INSTRUCTIONS: _____

_____

SECTION "3"

CHANGE: TEMPERATURE - NEW TEMPERATURE; DATE ACTION REQUIRED _____

_____

_____

OTHER INSTRUCTIONS: _____

_____

SECTION "4"

CHANGE: RELATIVE HUMIDITY - NEW SETTING; DATE ACTION REQUIRED _____

_____

_____

OTHER INSTRUCTIONS: _____

_____

*****ATTENTION - FOR ANY CHANGE IN DAYLIGHT DURATION OR THE START OF A NEW EXPERIMENT A NEW PROGRAM MUST BE SUBMITTED.

SIGNATURE: _____ DATE SUBMITTED: _____

APPENDIX 8

PREVENTATIVE MAINTENANCE

****FOR GREENHOUSE AND MAINTENANCE USE ONLY****

THIS CABINET WILL BE READY FOR RE-USE ON (DATE) _____

THIS CABINET WAS CLEANED AND READY FOR RE-USE (DATE) _____

SIGNATURE: _____ DATE: _____

THIS CABINET IS ON TEST DATE: _____ SIGNATURE: _____

TEMPERATURE SETTING: _____

IN THE EVENT OF A MALFUNCTION 1) call Carey Jackson (Maintenance - 395 or page)

2) after hours - call C. Jackson @ 345-2393

- if no answer, shut cabinet down and indicate on commissionaire's report

Start-Up

Unit/Room No.: _____ Date: _____

Previous temp.: _____ Lights required: _____

New temp. required: _____ Heaters required: _____

Humidity required: _____

Change reason: _____

High limit set	☐	Heater switches set	☐
Low limit set	☐	Temperature/humidity recorder	☐
Computer center notified ..	☐	Temperature program timer set	☐
Audible alarm on	☐	Humidity program timer set	☐
Circuit breakers/fuses	☐	Defrost limit set (max +7°C)	☐
Circulation fans	☐	Dampers on correct coil	☐
Aspirator fan	☐	Top defrost heater limit set (max. +10°C)	☐
Light switches set	☐	Bottom defrost heater limit set (max. +10°C) ...	☐
		Pilot lights operating	☐

APPENDIX 9A

Long-term averages and extremes of air temperature (°C), 1902-1985, Lethbridge

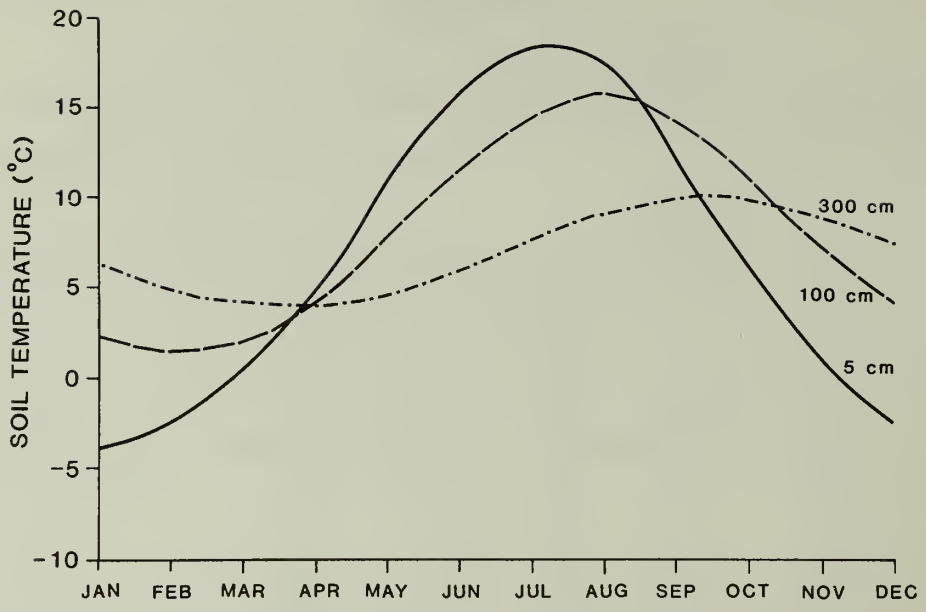
	Mean			Extreme			
Month	Max	Min	Daily	Max	Year	Min	Year
January	-3.0	-15.1	-9.0	17.8	1931	-43.0	1909
February	-0.4	-12.7	-6.6	19.7	1962	-42.2	1905
March	4.3	-8.3	-2.0	24.4	1906,66	-37.8	1947
April	12.4	-1.6	5.3	33.7	1906	-27.2	1940
May	17.7	3.6	10.6	33.3	1928	-12.8	1954
June	21.6	7.9	14.8	35.6	1933,36	-3.3	1951
July	26.0	10.3	18.1	39.1	1904	0.8	1910
August	24.9	9.1	17.0	37.2	1906	-1.4	1911
September	19.2	4.6	12.0	35.8	1950	-15.6	1934
October	13.9	0.0	7.0	30.0	1904,33,80	-26.1	1919
November	5.2	-6.9	-0.8	23.1	1908,40,49	-35.6	1912
December	-0.3	-11.7	-6.0	19.6	1908	-42.5	1924
Annual	11.8	-1.7	5.0	39.1		-43.0	

APPENDIX 9B

Frost data, 1902-1985, Lethbridge

	Extremes		
	Average	Earliest	Latest
Last frost in spring (0°C)	May 1	Apr 26 1940	Jul 3 1979
First frost in fall (0°C)	Sep 15	Aug 14 1928	Oct 14 1928
No. of frost-free days	117	80 (1951)	171 (1940)
Last killing frost in spring (-2°C)	May 7		Jun 2 1984
First killing frost in fall (-2°C)	Sep 25	Sep 3 1962	Oct 22 1984
No. of crop days	140	110 (1921)	178 (1940)

APPENDIX 9C



Mean soil temperature at three depths, 1967-1985, Lethbridge

APPENDIX 9D

Average monthly growing degree-days, heating degree-days, and corn heat units in the Lethbridge area

	Growing degree-days above 5°C and 10°C		Heating degree-days below 18°C	Corn heat units
January	1	0	851	0
February	4	0	666	0
March	8	0	634	0
April	45	9	383	0
May	159	60	221	308
June	273	141	106	518
July	369	240	29	658
August	337	204	48	616
September	194	93	168	0
October	83	25	323	0
November	12	2	560	0
December	2	0	729	0
Total	1487	774	4718	0

APPENDIX 9E

Long-term averages and extremes of precipitation and snowfall, 1902-1985, Lethbridge

Month	Mean	Median	Greatest precipitation (mm) Amount	Year	Least precipitation (mm) Amount	Year	Greatest snowfall (cm) Amount	Year
Jan	19.3	18.0	50.7	1978	0.3	1931	66.1	1978
Feb	17.1	17.1	55.1	1953	0.5	1977	55.1	1953
Mar	23.9	22.2	63.8	1933	2.5	1917	63.8	1933
Apr	32.4	27.5	112.5	1967	0.5	1902	136.9	1967
May	54.6	41.7	286.3	1902	2.3	1928	66.3	1903
Jun	72.4	64.5	207.5	1953	2.0	1985	20.3	1951
Jul	41.6	35.1	151.1	1902	1.5	1967	1.0	1914
Aug	41.2	32.1	168.1	1978	1.5	1969	trace	1952
Sep	41.2	31.4	123.4	1925	0.0	1948	69.3	1968
Oct	22.6	17.5	111.0	1946	0.0	1944	62.0	1933
Nov	18.6	14.0	73.2	1927	0.0	1917	73.2	1927
Dec	19.0	16.5	57.7	1933	0.0	1913	57.7	1933
Total	403.9							
Extremes			709.1	1902	193.8	1918	305.6	1933

APPENDIX 9F

Percent probability of growing season rainfall, Lethbridge

Month	Mean	Probabilities of receiving amounts (mm) greater than 10	20	30	40	50	60	70	80	90	100
Mar	23.9	85	57	23	12	6	1	-	-	-	-
Apr	32.4	85	63	43	24	18	17	9	6	4	2
May	55.3	98	88	71	55	37	32	26	21	16	11
Jun	73.5	99	91	82	68	60	55	45	41	33	27
Jul	42.1	94	74	56	44	34	26	18	12	7	4
Aug	41.0	85	70	52	41	33	24	17	11	10	5

APPENDIX 9G

Lethbridge sunshine data, 1909-1985

	Mean daily hours	Percent of possible	Maximum		Minimum	
			Hours/ month	Year	Hours/ month	Year
Jan	3.2	36	143	1985	43	1971
Feb	4.3	43	173	1931	74	1940
Mar	5.2	45	231	1912	90	1983
Apr	6.9	50	283	1934	103	1920
May	8.4	54	344	1928	136	1927
Jun	9.3	57	385	1917	207	1942
Jul	11.0	70	406	1933	251	1912
Aug	9.7	68	392	1969	220	1968
Sep	7.0	56	283	1938	114	1985
Oct	5.5	51	231	1952	101	1951
Nov	3.8	41	178	1917	61	1927
Dec	3.0	37	156	1913	45	1980
Annual extremes			2593	1943	2120	1942

APPENDIX 10

Standard Abbreviations

Celsius degree	°C	meter	m
centimeter	cm	metric ton	t
cubic centimeter	cm^3	micron	µm
cubic meter	m^3	microEinstein	µE
gram	g	milligram	mg
hectolux	hlx	milliliter	ml
kilogram	kg	millimeter	mm
kilolux	klx	milliwatt	mW
kilometer	km	nanometer	nm
Langley	Ly	square centimeter	cm^2
liter	l	square meter	m^2
lux	lx	watt	W

APPENDIX 11

Conversion factors

To Convert From*	To	Multiply By
Acres	hectares	0.404
Cubic feet/min	$m^3 min^{-1}$	0.0283
Cubic feet/min	liters min^{-1}	28.3
Cubic inch	cm^3	16.387
Cubic yard	m^3	0.764
Fathom	m	1.8
Feet/min	m min^{-1}	0.3048
Feet/min	m sec^{-1}	0.0051
Firkin	liters	34.1
Foot candle	lux	10.76
Furlong	m	201.2
Gallons/min	liters min^{-1}	3.78
Hectare	m^2	10,000
Inch	cm	2.54
Langley/min	cal $cm^{-2} min^{-1}$	1
Langley/min	mw cm^{-2}	69.7
Meters/sec	m min^{-1}	60.
Mile/hr	km hr^{-1}	1.6
Mile/hr	m min^{-1}	26.8
Ounce (avdp)	g	28.35
Ounce (U. S. Fluid)	ml	29.57
Pound (avdp)	g	453.6
Pound/in^2	mm Hg	51.7
Pound/in^2	g cm^{-2}	70.3
Pound/ft^2	kg m^{-2}	4.88
Pound/ft^3	kg m^{-3}	16
Quart (U. S. Liq.)	liters	0.946
Scruple	g	1.3
Square foot	m^2	0.0929
Square yard	m^2	0.836
Ton of regrigeration (U. S. Comm.)	Btu hr^{-1}	12,000
Ton of refrigeration	kg cal hr^{-1}	3023.95
Ton (metric)	kg	1000
Ton (short) = 2000 lb	kg	907.18
Yard	m	0.914
Watt/cm^2	cal cm^{-2} min^{-1}	14.34
Watt/cm^2	Joule sec^{-1} cm^{-2}	1
Watt/cm^2	erg sec^{-1} cm^{-2}	1 x 10^7

*To facilitate conversion, the time units are those customarily used in the past with the f. p. s. system; i.e., feet per min. x .3048 would convert to meters per minute in preference to m/sec.

(From Downs and Bonaminio 1976)

APPENDIX 12

Cornell mix

Make up in bushel tubs (35.2 liter)

Add in proportion by volume
- 2 parts peat moss
- 2 parts No. 3 grade (medium) vermiculite
- 1 part sand

To each tub add:
- 165 g $CaCO_3$
- 38 g 0-45-0 fertilizer
- 150 g Osmocote 18-6-12
- 1 g 300 FE sequestrene
- 2 g fritted trace elements

(Adapted from Boodley and Sheldrake 1977)

APPENDIX 13

Hoagland's no. 1 nutrient solution

All chemicals dissolved in distilled water.
Nutrient is made up in 20 liter plastic carboys.

Add
- Approximately 10 liters of distilled water
- 17 ml 1 M KH_2PO_3
- 17 ml Micronutrient solution*
- 33 ml 1 M $MgSO_4$
- 81 ml 1 M KNO_3
- 81 ml 1 M $Ca(NO_3)_2$
- 1.35 g Iron citrate dissolved by heating in approximately 1 liter distilled water
- Distilled water to make up to 20 liters

*Micronutrient solution
1 liter contains
- 2.86 g boric acid (H_3BO_3)
- 1.81 g manganese chloride ($MnCl_2 \cdot 4H_2O$)
- 0.22 g zinc sulphate ($ZnSO_4 \cdot 7H_2O$)
- 0.08 g copper sulphate ($CuSO_4 \cdot 5H_2O$)
- 0.02 g molybdic acid ($H_2MoO_4 \cdot H_2O$)

(Adapted from Hoagland and Arnon 1950)

APPENDIX 14

CONVERSION OF UNITS

Conversion of Photon Units to Radiometric Units

Conversion of quantum sensor output in $\mu E\ s^{-1}\ m^{-2}$ (400-700 nm) to radiometric units in $W\ m^{-2}$ (400-700 nm) is complicated. The conversion factor will be different for each light source, and the spectral distribution curve of the radiant output of the source (W_λ; $W\ m^{-2}\ nm^{-1}$) must be known in order to make the conversion. The accurate measurement of W_λ is a difficult task, which should not be attempted without adequate equipment and calibration facilities. The radiometric quantity desired is the integral of W_λ over the 400-700 nm range, or:

$$W_T = \int_{400}^{700} W_\lambda \, d\lambda \qquad (1)$$

At a given wavelength λ, the number of photons per second is

$$\text{photons } s^{-1} = \frac{W_\lambda}{hc/\lambda} \qquad (2)$$

where $h = 6.63 \cdot 10^{-34}$ joule-s (Planck's constant), $c = 3.00 \cdot 10^{8}$ m s^{-1} (velocity of light) and λ is in nm. hc/λ is the energy of one photon. Then, the total number of photons per second in the 400-700 nm range is

$$\int_{400}^{700} \frac{W_\lambda}{hc/\lambda} \, d\lambda \qquad (3)$$

This is the integral which is measured by the sensor. If *R* is the reading of the quantum sensor in $\mu E\ s^{-1}\ m^{-2}$ ($1\ \mu E\ s^{-1}\ m^{-2} \equiv 6.022 \cdot 10^{17}$ photons s^{-1} m^{-2}), then

$$6.022 \cdot 10^{17}\,(R) = \int_{400}^{700} \frac{W_\lambda}{hc/\lambda} \, d\lambda \qquad (4)$$

Combining Eq. (1) and Eq. (4) gives

$$W_T = 6.022 \cdot 10^{17}\,(Rhc) \frac{\int_{400}^{700} W_\lambda \, d\lambda}{\int_{400}^{700} \lambda W_\lambda \, d\lambda} \qquad (5)$$

To achieve the two integrals, discrete summations are necessary. Also, since W_λ appears in both the numerator and the denominator, the normalized curve N_λ may be substituted for it. Then

$$W_T = 6.022 \cdot 10^{17}\,(Rhc) \frac{\sum_i N_{\lambda_i} \Delta\lambda}{\sum_i \lambda_i N_{\lambda_i} \Delta\lambda} \qquad (6)$$

where $\Delta\lambda$ is any desired wavelength interval, λ_i is the center wavelength of the interval and $N_{\lambda i}$ is the normalized radiant output of the source at the center wavelength. In final form this becomes

$$W_T \approx 119.8\,(R) \frac{\sum_i N_{\lambda_i}}{\sum_i \lambda_i N_{\lambda_i}} \ W\ m^{-2} \qquad (7)$$

where R is the reading in $\mu E\ s^{-1}\ m^{-2}$.

The following procedure should be used in conjunction with Eq. (7).

1. Divide the 400-700 nm range in 'i' intervals of equal wavelength spacing $\Delta\lambda$.
2. Determine the center wavelength (λ_i) of each interval.
3. Determine the normalized radiant output of the source (N_{λ_i}) at each of the center wavelengths.
4. Sum the normalized radiant outputs as determined in Step 3 to find $\sum_i N_{\lambda_i}$.
5. Multiply the center wavelength by the normalized radiant output at that wavelength for each interval.
6. Sum the products determined in Step 5 to find $\sum_i \lambda_i N_{\lambda_i}$.
7. Use Eq. (7) to find W_T in $W\ m^{-2}$, where R is the quantum sensor output in $\mu E\ s^{-1}\ m^{-2}$.

The following approximation assumes a flat spectral distribution curve of the source over the 400-700 nm range (equal spectral irradiance over the 400-700 nm range) and is shown as an example.

Given: $i = 1$
$\Delta\lambda = 300$ nm
$\lambda_i = 550$ nm

$$W_T \approx 119.8\,(R)\left(\frac{N(550)}{550 \cdot N(550)}\right) = \frac{119.8(R)}{550} = 0.22(R)\ W\ m^{-2}$$

or

$$1\ W\ m^{-2} \approx 4.6\ \mu E\ s^{-1}\ m^{-2}$$

This conversion factor is within ±8.5% of the factors determined by McCree as listed in Table I (8).

Conversion of Photon Units to Photometric Units

To convert photon units ($\mu E\ s^{-1}\ m^{-2}$, 400-700 nm) to photometric units (lux 400-700 nm), use the above procedure, except

a) Replace Eq. (1) with

$$\text{Lux} = 683 \int_{400}^{700} y_\lambda \, W_\lambda \, d\lambda$$

where y_λ is the luminosity coefficient of the standard CIE curve with $y_\lambda = 1$ at 550 nm and W_λ is the spectral irradiance ($W\ m^{-2}\ nm^{-1}$).

b) Replace Eq. (5) with

$$\text{Lux} = (683)\,(6.022 \cdot 10^{17})\,(Rhc) \frac{\int_{400}^{700} y_\lambda \, W_\lambda \, d\lambda}{\int_{400}^{700} \lambda W_\lambda \, d\lambda}$$

c) Replace Eq. (6) with

$$\text{Lux} = (683)\,(6.022 \cdot 10^{17})\,(Rhc) \frac{\sum_i y_{\lambda_i} N_{\lambda_i} \Delta\lambda}{\sum_i \lambda_i N_{\lambda_i} \Delta\lambda}$$

d) Replace Eq. (7) with

$$\text{Lux} = 8.17 \cdot 10^{4}\,(R) \frac{\sum_i y_{\lambda_i} N_{\lambda_i}}{\sum_i \lambda N_{\lambda_i}}$$

e) Replace Step 4 with:

4a) Multiply the luminosity coefficient (y_λ) of the center wavelength by the normalized radiant output (N_λ) at that wavelength for each interval.

4b) Sum the products determined in Step 4a to find $\sum_i y_{\lambda_i} N_{\lambda_i}$.

The following approximation assumes a flat spectral distribution curve of the source over the 400-700 nm range (equal spectral irradiance over the 400-700 nm range) and is shown as an example.

Given: $i = 1$ to 31
$\Delta\lambda = 10$ nm
$\lambda_1 = 400, \lambda_2 = 410, \lambda_3 = 420 \ldots\ldots \lambda_{31} = 700$
$N_\lambda = 1$ for all wavelengths
$y_{\lambda_1} = 0.0004, y_{\lambda_2} = 0.0012, y_{\lambda_3} = 0.004 \ldots\ldots y_{\lambda_{31}} = 0.0041$

$$\text{Lux} = 8.17 \cdot 10^{4}\,(R) \frac{\sum_i y_{\lambda_i}}{\sum_i \lambda_i} = 8.17 \cdot 10^{4}\,(R)\left(\frac{10.682}{17050}\right)$$

Lux = 51.2 R, where R is in $\mu E\ s^{-1}\ m^{-2}$

Or,

$$1000\ \text{lux} = 1\ \text{klux} = 19.5\ \mu E\ s^{-1}\ m^{-2}$$

(From LI-COR 1979)

Top left. The main floor phytotron at the Lethbridge Research Station.
Top right. Examining plant in a virus-vector chamber.

Middle left. Barley growing in cylinders of soil.
Middle right. Mature wheat in a propagation room.

Bottom left. Corn in a high-ceiling growth chamber.
Bottom right. Pollinating wheat in a propagation room.